AN HISTORICAL STUDY OF CHANNEL CHANGE IN THE BELL RIVER, NORTH EASTERN CAPE

THESIS
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by

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ABSTRACT

Channel instability has occurred in the Bell river, north eastern Cape, in the form of meander cutoffs, incipient meander cutoffs, channel straightening and general channel instability. Recent cutoffs occurred in 1974 and 1988. The study examines the spatial and temporal controls of channel form and pattern in the Bell river in order to assess the causes of channel instability. From the 17 km surveyed stretch, it was found that the main spatial controls of channel form were riparian vegetation density and channel bed material. Discharge as estimated in the field was not the main controlling variable of channel form. Two distinct groups of stream beds were identified from the survey; an upper gravel-bed stream and a lower sand-bed stream. These sites displayed distinct form ratios, channel gradients and bed material characteristics. The incidences of major channel instability were identified as being the transitional zone between the two reaches. Examination of temporal controls of channel form included climatic trend analysis and catchment sediment production analysis. Rainfall analysis indicated that no long term progressive trends in the annual or seasonal data existed. Distinct wet and dry cycles occur with peaks every 16 to 19 years. Wet cycles are the result of an increase in the frequency of daily events rather than in the magnitude of events. Flow record analysis demonstrated the relationship between regional discharge and upper catchment rainfall. Coincidence of peak flows and channel straightening were also noted. Soil erosion surveys showed that erosion had increased in the catchment and that accelerated erosion were probably the result of overstocking and poor veld management.

It was concluded that channel changes in the Bell river are possibly the result of anthropogenic influence in catchment and channel processes. Increased sediment production to the channel resulted in channel aggradation with attendant instability. The plantation of riparian vegetation led to perimeter stability in the short term at flows less than bankfull discharge, but served to reduce cross-sectional area in the long term, thereby increasing the potential for flooding, meander cutoffs and channel change.

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

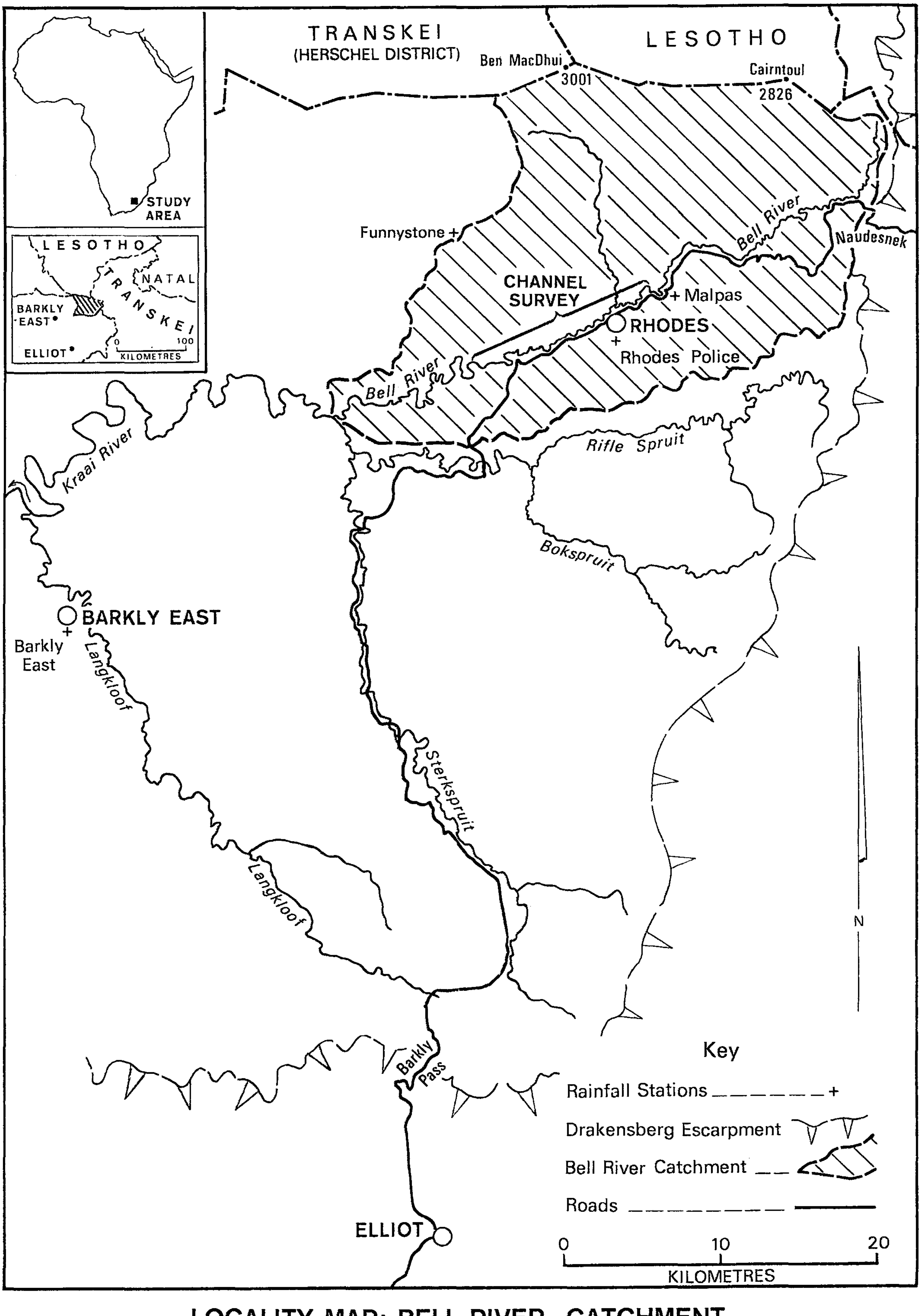
Although the study of fluvial geomorphology is well established internationally, very little work has been carried out on South African fluvial systems (Dardis *et al*, 1988a; Dollar, 1990). This is despite the fact that South African fluvial systems have been subject to major changes, either through indirect effects such as land-use changes (Bruwer and Ashton, 1989; Vogt and Moon, 1989) or more direct effects such as channel impoundments and engineering schemes (Dollar, 1990). Even less work has been undertaken to determine the relationship between channel form and control variables in South Africa (Rowntree and Wadeson, 1991). This project will attempt to draw together the effects of catchment land-use and management practices (catchment variables) and local spatial control variables (channel variables) on determining channel form, pattern and potential instability in a South African fluvial system, the Bell river.

Changes imposed on a fluvial system, be they natural or man induced, are absorbed by the system through a series of channel adjustments (Simon, 1988). The Bell river, near Rhodes in the north eastern Cape province of South Africa, a tributary of the Kraai river (Figure 1.1) in the Orange river drainage system, has shown channel instability as evidenced by meander cutoffs, incipient meander cutoffs and general channel instability.

Traditionally, fluvial theory has seen river channel changes in the context of changing energy environments (Warner, 1987). Rivers possess the intrinsic potential to initiate change (Schumm, 1979). Most work on river channel changes in recent years have either concentrated on the importance of climatic changes in altering channel form (Erskine, 1986), or more importantly, anthropogenic influence (Beaumont, 1978; Park, 1981). River systems are seen as dynamic, open, sensitive systems, with energy renewals operating in the form of feedback loops in an attempt to maintain equilibrium conditions.

Two main factors acting interdependently operate within the fluvial system determining firstly, channel form and pattern, and secondly the potential for changes in channel form and pattern. These are catchment factors and channel factors (Baker, 1977). Together these determine channel form and process, both within a spatial and a temporal context. Channel factors determine the nature and type of channel change. Catchment factors determine the magnitude and extent of the change. Channel change may occur in response to a single variable or combination of these variables.

Figure 1.1: Study Area, Bell River



LOCALITY MAP: BELL RIVER CATCHMENT

1.2 EVIDENCE FOR CHANNEL CHANGE IN THE BELL RIVER AND BRIEF THEORETICAL CONTEXT

Instability in the form of meander cutoffs and channel widening has occurred in the Bell river, resulting in a shift from a meandering to a straighter, divided channel (Rowntree and Dollar, 1992) (Figure 1.2). Aerial photographs and recent channel surveys have indicated evidence for channel straightening and braiding. Sequential aerial photographs for 1952, 1969 and 1975 show the development of a series of meander cutoffs and general channel instability. Decreased channel sinuosity and increased gradient changes have accompanied channel shifting (Chapter 4). A recent cutoff occurred on the farm Earlstone. This is being monitored by means of fixed point cross-sectional survey (Figure 1.3). The site was surveyed at six monthly intervals, April 1990, October 1990, April 1991 and November 1991.

A number of abandoned channels have been identified in this reach through aerial photography work and field surveys. Figure 1.3 is a sketch map of the area. Prior to 1969, the channel followed the path shown in A. Between 1969 and 1975 (probably 1974) channel straightening occurred with the new channel flowing in the direction of arrow B. This channel pattern was maintained until 1988, when a storm event initiated further channel straightening, with the present channel flowing in the direction of arrow C. The last 30 years have therefore witnessed considerable channel instability and straightening, not only for the particular monitoring stretch, but for other parts of the channel (see Figure 1.2). It was decided to monitor the most recent area of instability with fixed point cross-sectional surveys. Surveys were undertaken on a six monthly basis. A total of 9 transects in the reach were identified and fixed (see Appendix A). During the past 2 years sequential surveys were undertaken with very little significant movement being observed. This may be due to the fact that no large discharge event has occurred in this time.

Channel straightening and general channel instability in modern time (0-100 years) is thought to be related to the dominant sediment and discharge regimes, with factors such as geology, relief, valley dimensions and palaeohydrology seen as independent variables (Schumm and Lichty, 1965; Lewin *et al*, 1988). Schumm (1969) developed a qualitative model demonstrating the direction of morphological response to particular combinations of discharge and sediment yield (Table 1.1). From the evidence presented in this table, channel change in terms of sinuosity, gradient, form ratio and so on are all responses to the combined variations of changing discharge and sediment yield, which are functions of catchment processes.

An increase in catchment erosion and runoff may result in an increased sediment load with concomitant effects such as downstream aggradation of the channel and increased flood peaks and frequency (Schumm *et al*, 1984). Debano and Schmidt (1989) have shown the delicate interrelationship that exists between catchment hydrology, soil erosion and catchment condition, as affected by grazing management and related activities.

Table 1.1: Qualitative Method for Channel Change Analysis (After Schumm, 1969)

QUALITATIVE MODEL OF CHANNEL METAMORPHOSIS

$Q^{+} - w^{+} d^{+} F^{+} L^{+} s^{-}$ $\quad\quad$ $Q^{-} - w^{-} d^{-} F^{-} s^{+}$

$Qb^{+} - w^{+} d^{-} F^{+} L^{+} s^{+} P^{-}$ $\quad\quad$ $Gb^{-} - w^{-} d^{+} F^{-} s^{-} P^{+}$

$Q^{+}Gb^{+} - w^{+} d^{+-} F^{+} L^{+} s^{+-} P^{-}$

$Q^{-}Gb^{-} - w^{-} d^{+-} F^{-} L^{-} s^{+-} P^{+}$

$Q^{+}Gb^{-} - w^{+-} d^{+} F^{-} L^{+-} s^{-} P^{+}$

$Q^{-}Gb^{+} - w^{+-} d^{-} F^{+} L^{+-} s^{+} P^{-}$

Where: Q = discharge index
Gb = bed load
w = width
d = depth
F = form ratio
L = meander wavelength
s = channel gradient
P = sinuosity

Figure 1.2: Channel Straightening in the Bell River for Three Dates: 1952, 1969 and 1975

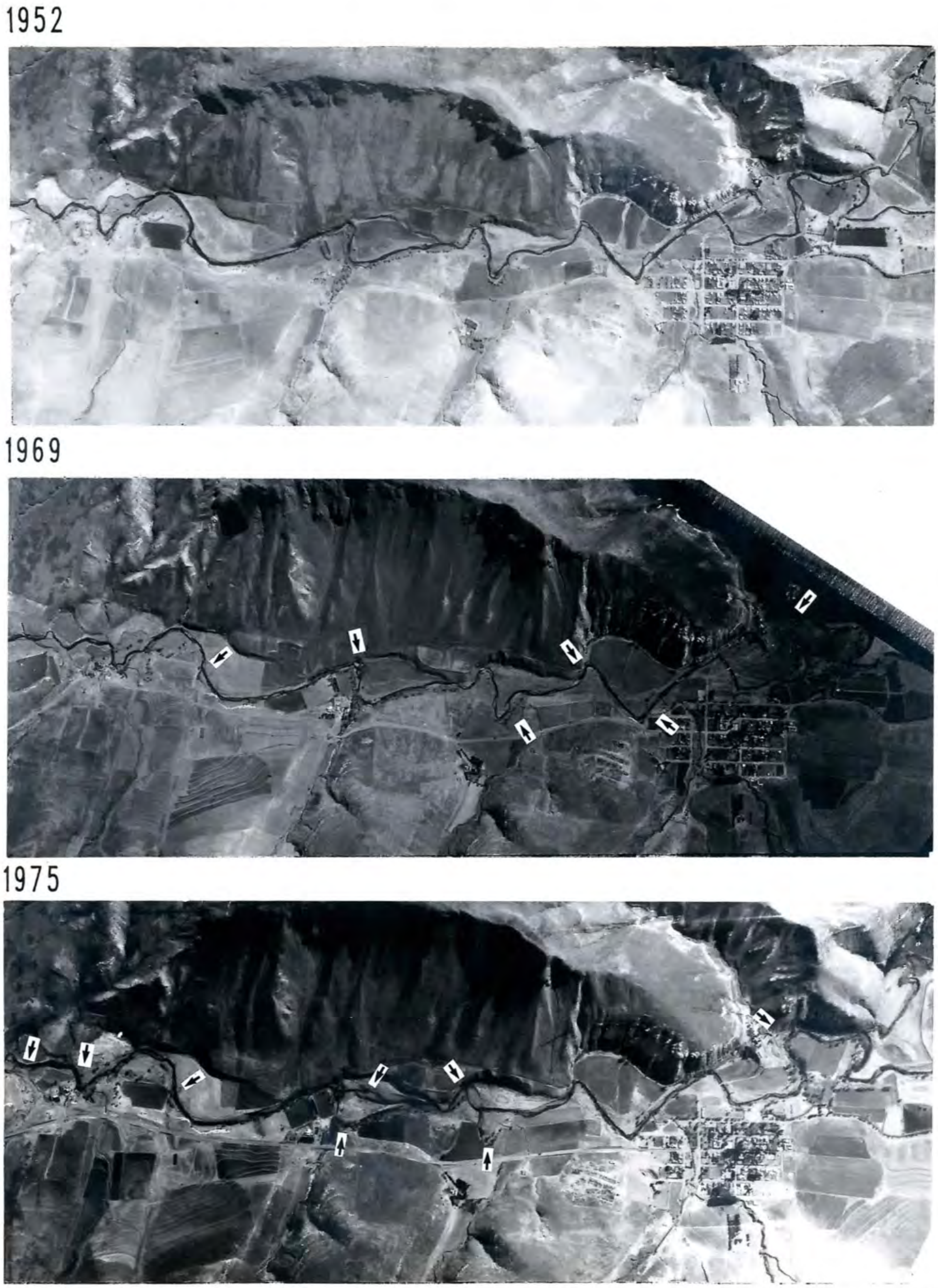
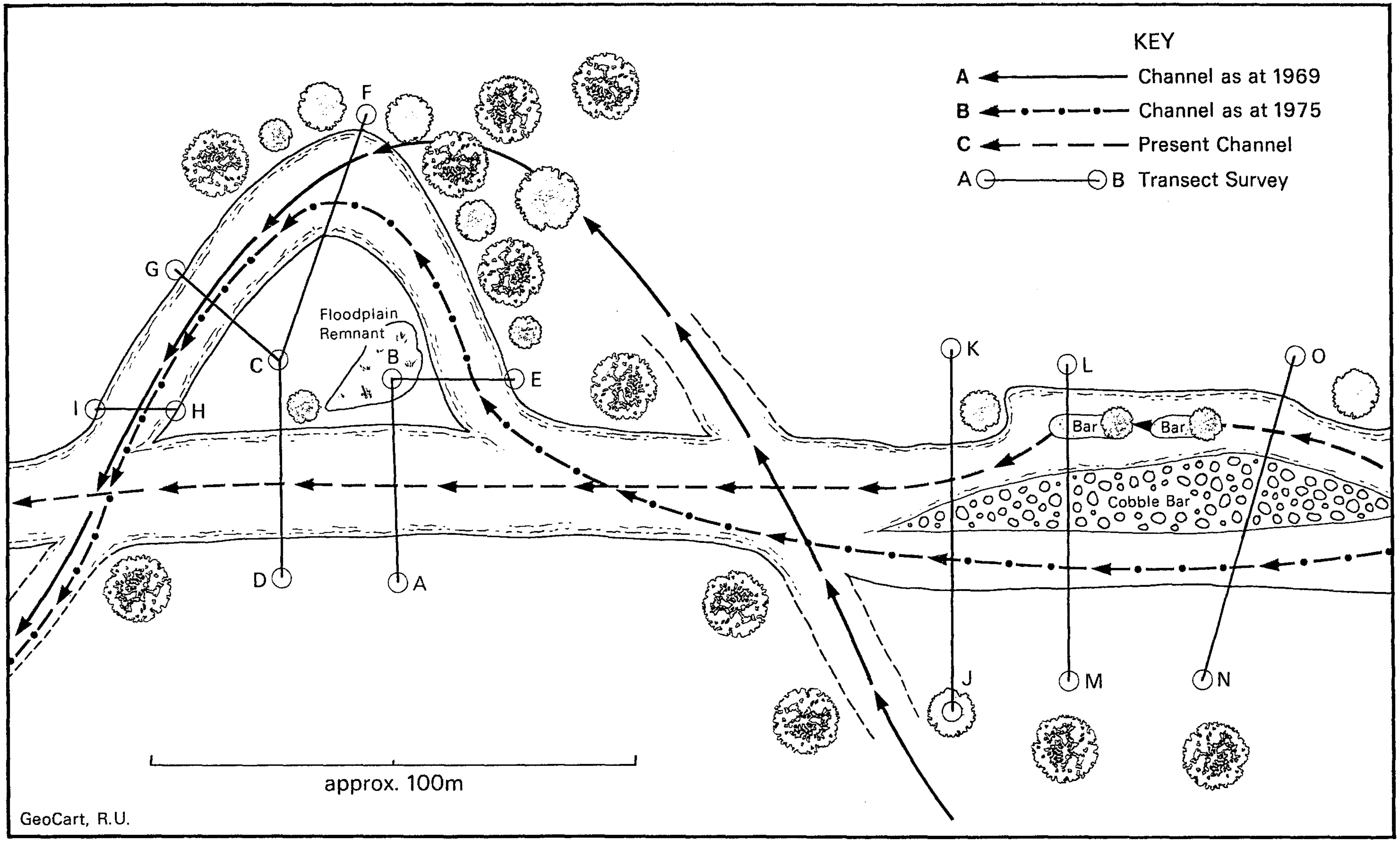


Figure 1.3: Location of Fixed Point Survey, Bell River



1.3 GENERAL RESEARCH AIMS AND OBJECTIVES

1.3.1 Research Aims

The aims of this research are:

1) To determine river channel changes in the Bell river in terms of channel form and channel pattern in the last 40 years.

2) To assess the possible causes of channel instability. These may include altered hydraulic and sediment regimes due to catchment land-use and management, climatic change or intrinsic thresholds that may have been exceeded.

1.3.2 Research Objectives

The following objectives have been identified:

1) To determine channel pattern and form change from aerial photographs and field surveys.

2) To monitor current changes in channel geometry and plan at selected sites using fixed point transect surveys.

3) To determine bed and bank material characteristics at selected sites.

4) To determine valley and channel slope.

5) To determine channel form variables, including width, depth, width-depth ratio, cross-sectional area, channel gradient and estimated bankfull discharge at selected sample sites.

6) To determine riparian vegetation characteristics.

7) To analyze climatic records in order to determine the existence of progressive climatic trends in annual, seasonal and daily rainfall.

8) To analyze flow records in order to document regional floods that have occurred.

9) To determine sediment sources from aerial photographs and ground surveys.

10) To determine possible changes in catchment land-use and management.

1.4 TEMPORAL CONTEXT OF RESEARCH

The time span in which the research is considered is of extreme importance. It should be stressed that the identification of cause and effect in the Bell river will be viewed in the context of present/modern time (Schumm and Lichty, 1965) similarly expressed as engineering time (0-100 years, Lewin *et al*, 1988). The distinction between cause and effect relationships is a function of time and scale. The factors determining channel form and process can be viewed either as dependent or independent, depending on the temporal context in which they are considered (see Table 1.2).

During engineering time, the assumption is that variables such as geology, valley slope and palaeohydrology are independent variables, to which the rivers have adjusted their equilibrium. River adjustment in engineering time is to the dominant sediment and discharge regimes. It is in this temporal context that channel changes in the Bell river are considered.

Table 1.2: The Status of River Control Variables Considered in Different Temporal Scales (after Schumm and Lichty, 1965)

RIVER VARIABLES	STATUS OF VARIABLES DURING DESIGNATED TIME SPAN		
	GEOLOGIC	MODERN	PRESENT
Time	Independent	Not Relevant	Not Relevant
Geology	Independent	Independent	Independent
Climate	Independent	Independent	Independent
Vegetation	Dependent	Independent	Independent
Relief	Dependent	Independent	Independent
Palaeohydrology	Dependent	Independent	Independent
Valley Dimensions	Dependent	Independent	Independent
Channel Morphology	Indeterminate	Dependent	Independent
Observed discharge of water and sediment	Indeterminate	Indeterminate	Dependent
Observed flow characteristics	Indeterminate	Indeterminate	Dependent

1.5 THE STUDY SITE

The Bell river in the north east Cape Drakensberg forms part of the headwaters of the Orange river drainage system. It drains a mountainous catchment with an area of approximately 424 square kilometres. The altitude of the catchment ranges from 3001 metres (a.m.s.l) at the headwaters of the catchment, to 1720 metres at the mouth of the catchment. Mean annual rainfall experienced in the catchment ranges from 700 to 1300 mm, with most of the rainfall occurring during the summer months (October to March). Details of catchment rainfall are presented in Chapter 6. The catchment has been used extensively for grazing by White commercial farmers since the 1890s (Hugo, 1966). Floodplain areas are cultivated and used as fodder for livestock.

Plate 1.1: Typical View of the Bell River Catchment

1.5.1 Catchment Geology

The geology of the area forms part of the Karoo system, Stormberg series. Pink, massive, fine grained, sedimentary Clarens sandstones are overlain by Drakensberg basalts which are compact amygdaloidal lavas (Du Toit, 1912; Pemberton, 1978).

The volcanic basalts occur in the higher lying regions of the catchment, whereas the cave sandstones are found in the lower lying valley regions towards the mouth of the catchment. The volcanic clasts tend to be structurally weaker than the sedimentary rocks, which makes the former more susceptible to *in situ* weathering, as well as weathering and abrasion in the channel (Townshend, 1991). Soil depth in the upper catchment on the steeper slopes is limited, deep soils and colluvial sediments do however occur on the footslopes and in the lower lying floodplain areas.

1.5.2 Slope Sediments

Many of the lower, south facing slope sediments in the Rhodes district are thought to have been under the influence of periglacial activity (Lewis and Hanvey, 1988). These sediments reveal a stratified nature, with deposition believed to have resulted from nivation, gelifluction and slope-wash processes. More recently Lewis and Hanvey (1991) suggested that these deposits indicated progressive accretion through cryogenic processes inferred to be freeze-thaw activity, sheet wash and solifluction. Hanvey *et al* (1986) suggested that they are of Quaternary origin, due to the unconsolidated nature of the sediments and the fact that they were not highly weathered. Sediment size ranges from large boulders to fine sand. Due to the unconsolidated nature of the sediments, they are highly erodible once the protective vegetative cover has been removed. North facing slopes consist of colluvial deposits typical of southern Africa (see Watson *et al*, 1984 for a full description) which produce generally finer material (< 2 mm).

1.5.3 Catchment Vegetation

Vegetation in the catchment is dominated by climax grassveld. The dominant grassveld type is *Themeda-Festuca Alpine Veld* (Acocks, 1953, No. 58), which is the common grassveld of the Drakensberg range between the altitude of 1800 to 2100 metres. The vegetation tends to be short and dense and ranges from sour to mixed grazing. The dominant species of this vegetation type is *Themeda triandra*. Acocks (1975) writes that the main effect of mismanagement of this veld is to change the vegetation to a *Karroid False Fynbos* (This has been noted in several parts of the Bell river catchment).

The second grassveld type that occurs is *Cymbopogon-Themeda Veld* (Acocks, 1953, No. 48). This occurs in the lower lying regions of the catchment, along the valley floors. The dominant species is *Themeda triandra*, with *Eragrostis chloromelas triandra* and *Microchloa caffra* increasing with increased grazing pressure. Chapter 6 will describe grazing strategies and veld management in more detail.

Riparian vegetation in the catchment has changed since the introduction of woody vegetation. The stream banks are occupied by two willow species, *Salix caprea* and *S. babylonica*. These trees were planted by riparian land owners to stabilize the channel. *S. babylonica* was first planted in Rhodes village around 1917. *S. caprea* was introduced in the 1950s in response to advice from the Agricultural Extension Service who stated that this would lead to channel stabilization. *S. caprea* has spread considerably since then and occupies considerable lengths of the channel (Plate 1.2).

Plate 1.2: Woody Riparian Vegetation in the Bell River

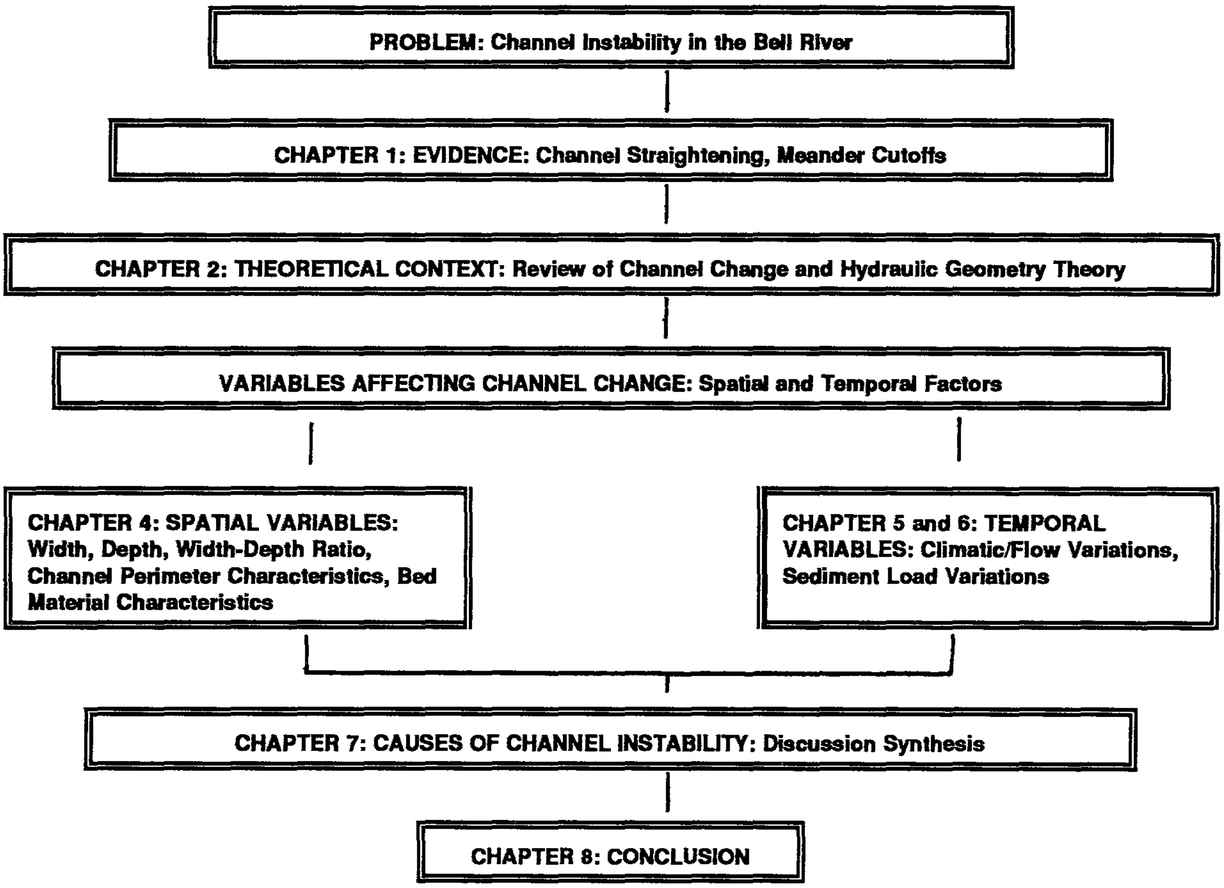
1.6 THESIS OUTLINE

A summary of the thesis structure is presented in Figure 1.4. Chapter 2 provides a theoretical framework within which the research is conducted. The theoretical framework reviews work undertaken by other authors on channel change and traditional hydraulic geometry theory. Limitations of conventional wisdom are also discussed. Chapter 3 outlines the overall research framework, with a discussion on the methodological approach taken in this research. Based on the theoretical review, Chapters 4, 5 and 6 examine spatial and temporal control variables affecting channel form and pattern in the Bell river. Chapter 4 deals essentially with the spatial controls determining the potential for channel change, including variables such as width, depth, width-depth ratio, bed material, estimated bankfull discharge and channel perimeter conditions.

Chapters 5 and 6 consider the temporal or catchment controls on the Bell river. Chapter 5 examines the possibility of a progressive climatic change in the Bell river catchment and it's possible consequences for channel change. Annual seasonal and daily data rainfall are considered. Chapter 6 deals with the possibility of an increased sediment load to the channel. This is determined through the use of aerial photographs to map soil erosion for sequential dates for the catchment. Changing land-use, stocking rates and management are also considered.

Having determined the spatial (Chapter 4) and temporal (Chapter 5 and 6) control variables affecting the potential for channel change, Chapter 7 synthesizes the results obtained in order to assess the causes of channel change in the Bell river. Chapter 8 serves as a conclusion to the study, and discusses study problems and limitations, the contribution of the study to the subject and further research recommendations.

Figure 1.4: Flow Diagram Indicating the Structure of Research



CHAPTER 2

THEORETICAL REVIEW

2.1 INTRODUCTION

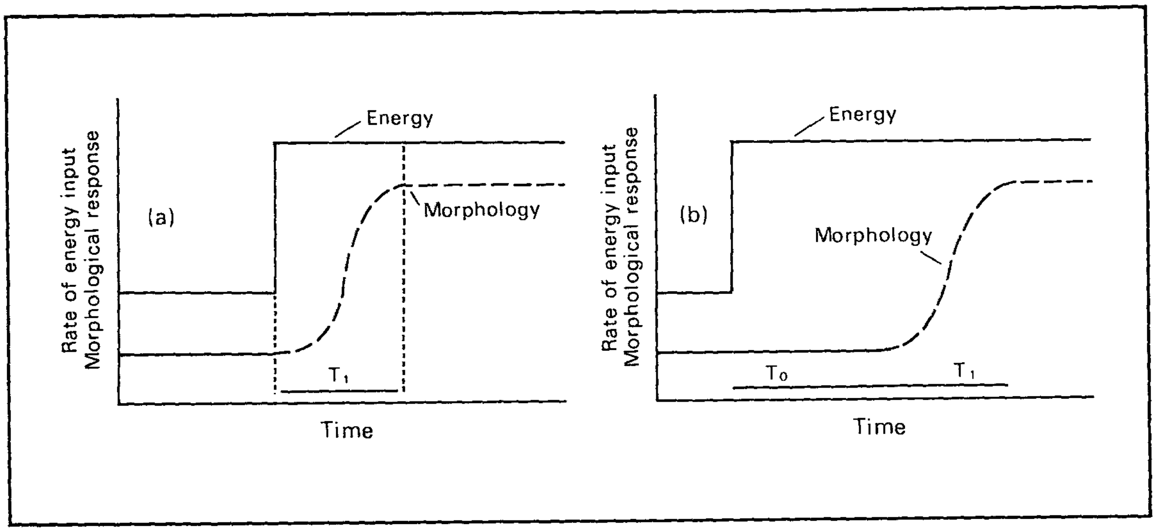
The aim in this chapter is to review research work and related theories on channel change in order to provide a framework within which channel change in the Bell river can be analyzed. Channel change refers not only to a change in channel geometry, but also a change in channel pattern. Maizels (1988) refers to channel change as a change in the form, pattern or sediment regime of a channel, occurring over any spatial or temporal scale.

Changes imposed on a fluvial system caused either by allogenic (external variables) or autogenic factors (internal variables) (Lewin, 1977), are absorbed by the river system and translated through a series of channel adjustments (Knighton, 1987; Simon, 1988). A number of authors have argued that the channel form at any point along the channel is either the result of upstream control variables such as climate, lithology, land-use and basin physiography (drainage basin factors), or local factors such as slope gradient and boundary conditions (channel factors). Together these determine the sediment and hydraulic regime of the channel, and thus channel planform and geometry (Schumm, 1969; Knighton, 1977; Hickin, 1983; Hey, 1986; Knighton, 1987; Kochel, 1988; Carling, 1988; Yang and Malinas, 1988; Kellerhals and Church, 1989; Jiongxin, 1991).

An important theme in channel change theory is that of equilibrium. The notion of equilibrium is based on the assumption that over a given time period a river will adjust it's pattern, geometry and planform in accordance with a climatically controlled runoff and sediment regime (Wolman and Gerson, 1978; Petts and Foster, 1985). Allen (1974) describes equilibrium as the relationship between energy supply to the system (independent variable) and it's morphological response (dependent variable). Schumm and Lichty (1965) speak of dynamic equilibrium in which form and process are in a steady state of balance. It should be stated that dynamic equilibrium only occurs in what Schumm and Lichty (1965) call modern and present time (0 - 100 years), or engineering time as expressed by Lewin *et al* (1988). Beyond this time, the concept of dependent and independent variables depends on the time span in which they are considered.

A change in energy input may not, however, be followed by an immediate morphological response. A possible cause of this delay is the existence of a 'reaction time' (Allen, 1974), that is, the time separating the change of energy input and the (channel) response. Conversely what may occur is 'relaxation time' where changes in morphology may lag behind a change in the rate of energy supply (see Figure 2.1).

Figure 2.1: Response and Relaxation Time (After Allen, 1974)



Channel change inherently implies a change in channel pattern and/or channel geometry. Rivers have traditionally been classified either as straight, meandering or braided (Selby, 1985; Morisawa, 1985). Straight channels are rare but short sections of rivers are sometimes classified as straight (Strahler, 1975). Meandering rivers have sinuous channels while braided streams have several channels which are divided around coarse gravel sediment bars (Chorley *et al*, 1984; Mangelsdorf, *et al*, 1990). The overall problem in channel pattern classification is the lack of an acceptable classification system, as all channels show features of both meandering and braiding (Carson, 1984). Pattern change involves a change from meandering to braided, braided to meandering or general channel straightening.

Stream channel beds can generally be classified as bedrock, sand or gravel streams (Schumm, 1963; Kellerhals *et al*, 1976; Mosley, 1987; Howard, 1987). Sandy beds (grain-size range 0.625-2.0 mm) are dominated by sand with small percentages of gravel, narrow grain size range, relatively deeper and narrower channels and high rates of sediment transport (Simons and Simons, 1987). Gravel-bed channels (grain-size range 2-64 mm) are dominated by gravel with small percentages of sand, coarse detritus, with wider, shallower, more unstable channels and lower sediment loads (Church, 1980). Downstream changes in channel types are usually abrupt (Knighton, 1987). The most common spatial transition is from headwater coarse-bed channels to downstream sand-bed channels (Ferguson, 1987).

Gravel-bed streams do not respond easily to changes in discharge as greater energy is required for transportation (Newson, 1980; Simons and Simons, 1987). Sand-beds respond more rapidly to imposed changes. For this reason Carson (1984) concluded that there can be no single threshold for discharge-slope functions for braiding, but rather a range of thresholds increasing with bed material diameter.

2.2.5 Perimeter Conditions

Vegetation and bank material play important roles in determining channel pattern and geometry (Thorne and Osman, 1988; Thorne, 1990, 1991; Rowntree, 1991b). Bank retreat occurs by a combination of flow erosion and mass failure under gravity (Thorne and Osman, 1988), with rate of retreat depending on bank material characteristics and flow at the base of the slope. Thorne (1991) found that bank widening was caused by base erosion and bed scour. Widening occurs when failure on one bank is not matched by aggradation of the opposite bank (Thorne, 1988).

Destruction of bank vegetation in a stream in eastern Oregon (Elmore and Beschta, 1987) led to channel instability and widening. Burton *et al* (1989), have shown how the destruction of bank and riparian vegetation has led to stream erosion and unstable channel banks, resulting in a wider and shallower channel. Schumm and Lichty (1965) have shown that the variations of width in the Cimarron river depends on wet and dry cycles and associated vegetation growth. The river narrows during wet years with the growth of vegetation and the absence of major floods. Floods following dry years with greatly reduced vegetation resulted in channel width increase.

Whereas vegetation has an undeniable effect on channel form, no simple cause and effect relationship exists. Vegetation can serve to enhance or reduce channel stability. Bank vegetation may serve to diminish near bank velocities and increase resistance to transport through binding the soil (Rowntree, 1991c). Aggradation at the bank face caused by vegetation may induce channel narrowing (Thorne, 1990). Thorne and Osman (1988) have noted that bank vegetation may reduce the effectiveness of flow erosion by one or two orders of magnitude.

The type and condition of vegetation plays an important role in bank stability. Low biomass vegetation such as grasses and shrubs enhance soil stability through the influence of roots and rhizomes. This type of vegetation does not eliminate deep seated failures however (Thorne and Osman, 1988). Trees may produce two types of results, firstly, heavy biomass trees may promote bank failure through surcharging, or older or dead trees with rotting roots may reduce soil cohesion, or induce soil piping (Thorne and Osman, 1988). Secondly, trees such as willows, with a dense mat of roots strongly binds the material reducing deep seated failure (Thorne, 1988; Rowntree, 1991c). Bank failure in this context would require a deep failure line beneath the mat of roots.

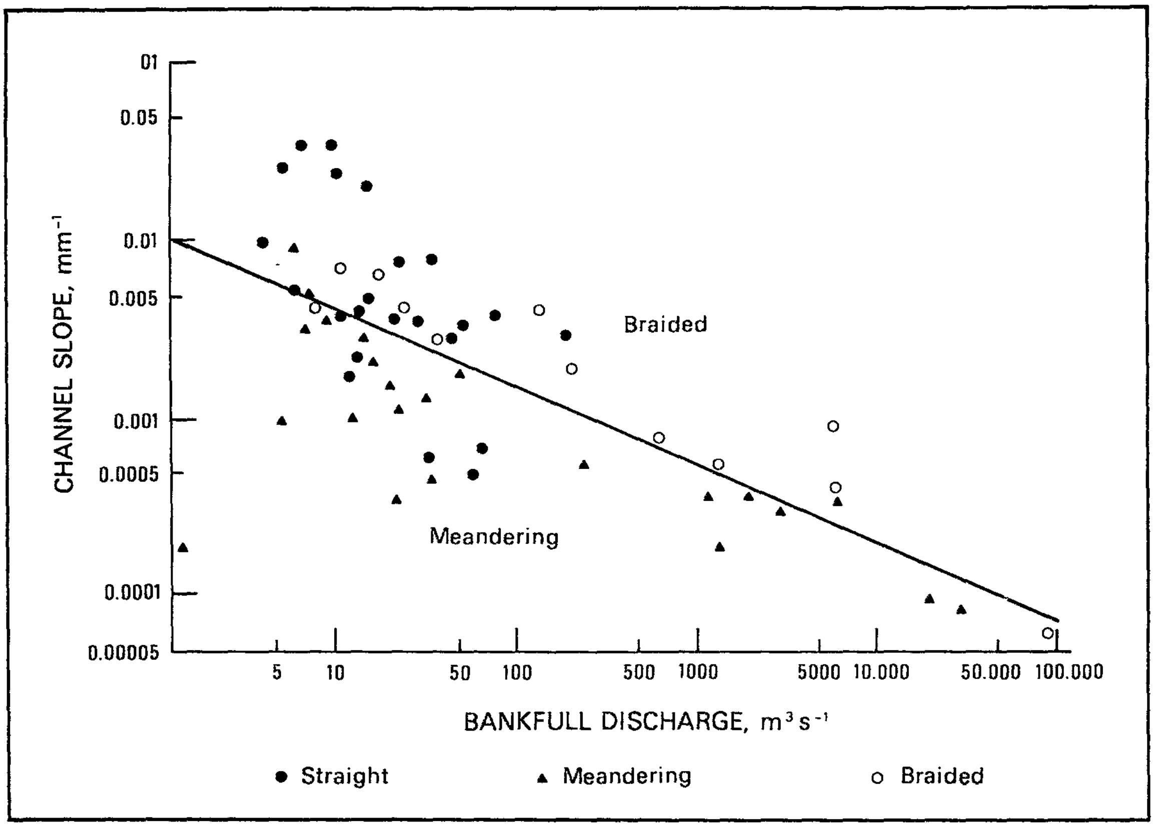
Vegetation may in fact lead to aggradation of the channel shelf, through lowering flow velocities inducing deposition (Rowntree, 1991c). This accretion further protects the bank from erosion. The effect of this may be to reduce channel capacity, resulting in a greater potential for flooding.

The percentage of silt and clay in the channel banks has important implications for channel form and has been related to the total sediment load (Schumm, 1969). Schumm (1960) has shown that channel banks with high silt-clay percentages are relatively narrower and deeper than those channels with low silt-clay percentages which tend to be wider and shallower. Channel banks are more cohesive when they display a higher silt-clay percentage, which is also a measure of their erosional resistance. In stratified banks, the maintenance of channel width depends on the strength of the different layers, particularly the basal layer, the erosion of which may induce block failure and slumping due to gravity (Knighton, 1987).

2.2.6 Meandering and Braiding Thresholds

The concept of a threshold slope for braiding (discharge-slope) which separates braided channels from meandering ones is well known (Leopold and Wolman, 1957; Schumm and Khan, 1972; Begin *et al*, 1981). The relationship of slope to discharge has been used by Leopold and Wolman (1957) to determine potential stream pattern (see Figure 2.2).

Figure 2.2: Channel Pattern Determined through Leopold and Wolmans (1957) Slope-Discharge Threshold



Lewin (1989) has pointed out that simple thresholds between straight/meandering and braided channels do not take into account the fact that channels with coarse sediment require higher stream power for transportation than sand-bed streams, and should therefore plot higher on the slope discharge graph. Lewin's (1989) work concurs with that of Carson (1984) who found that there was no single slope-discharge threshold for braiding, but rather that thresholds increased with bed particle diameter, and that thresholds for braiding for gravel-beds are greater than for sand-beds.

Thresholds are also often affected by channel armouring. During the rising limb of the hydrograph, transport and entrainment may be limited by the armour layer. Only when the threshold for entrainment is exceeded, will sediment be mobilized (Bathurst, 1987). Recently Newson (1992) has criticized the concept of thresholds and has stated "thresholds ... (are) a deceptively broad term with it's use highly dependent on the perspective of the user" (Newson, 1992, pp. 3). Newson makes the point that no single threshold exists and that a number of factors influence thresholds including biogenic and land-use impacts.

Renning-Roswell and Townshend (in Petts and Foster 1985), found that while most channel slopes are strongly correlated to drainage area, local slopes are correlated to bed material size, with coarse bed material associated with steep local slopes and wide shallow channels.

2.3 CHANNEL FORMING DISCHARGE

Wolman and Miller (1960) and Pickup and Warner (1976) stated that the geomorphic effectiveness of extreme events can be measured by a) the amount of work done on the landscape, and b) the effect on the landscape. This was borne out by the finding that in humid areas, the relative amount of work achieved by a single catastrophic event was not as great as the more frequent smaller magnitude events.

As discharge was thought to be the most important variable affecting channel form and pattern, an attempt was made to describe the range of flows most prominent in determining channel form (Williams, 1978). This led to the concept of dominant discharge as described firstly, by Wolman and Miller (1960) and later, by Pickup and Warner (1976). Dominant discharge is found to occur on average between 1 and 5 years in most streams (Pickup and Warner, 1976). Wolman and Miller (1960) found that most sediment was transported by flows of low to moderate magnitudes. This entrenched the concept that the magnitude and frequency of discharge events (Pickup, 1976) determined the condition of the channel (Knighton, 1977; Charlton *et al*, 1978). Dominant discharge was seen by Bray (1975) as the flow that would form and maintain the form and properties of the channel.

Erskine (1986) and Warner (1987) have reported fairly extensively on progressive changes in rainfall in Australia. The rainfall pattern is dominated by sequential years of above and below mean annual rainfall, with years of above mean rainfall referred to as Flood Dominated Regimes (FDR) and years of below mean annual rainfall termed Drought Dominated Regimes (DDR). Channel adjustment is often to floods occurring in FDRs. Therefore channel form may be in adjustment to the type of rainfall regime (FDR or DDR) experienced at a particular time.

In the Patuxent river in Maryland major floods (50 and 100 year R.I) in 1971 and 1972 caused major channel widening, but by 1974 smaller floods had totally reconstructed the channel (Gupta and Fox, 1974). The implication of this is, that for channel change to occur, a change in the hydraulic regime of the channel (magnitude and frequency) would be required which would result in a change in channel form, with the channel equilibrating to the new dominant discharge.

Workers in more recent years have begun to question the validity of the traditional regime theory. While channel form was controlled primarily by discharge in the upper reaches of a river, Ebisemiju (1991) found that site specific factors were the major controls in the middle and lower reaches of the Eleni river in Nigeria.

Lewin *et al* (1988) stress that the regime approach should be seen as a concept describing river form/pattern over a period of around a hundred years. Chang (1988) emphasized the importance of viewing regime theory in it's correct temporal context, so that the distinction between independent and dependent variables becomes a matter of time scale. Further, the concept of dominant discharge, and magnitude and frequency of events determining channel form is now being questioned (Carson, 1984). Many upland streams have the potential for catastrophic responses to large floods (Werritty and Ferguson, 1980; Carling, 1987; Carling, 1988a). In fact large floods may be responsible for changing channel morphology from a state of dependence to a state of independence (Newson and Macklin, 1990).

While dominant discharge may be responsible for the transportation of most of the sediment, it was not found to be the same as that for maintaining channel form and capacity. The principle of relative frequency events of low magnitudes accomplishing the most geomorphic work was found to refer to the transport capacity of the stream, rather than it's ability to institute change. Smaller floods are more important in returning the channel to some form of equilibrium, after exceedence of threshold limits by major floods (McEwan, 1989).

Baker (1977) stated that the concept of frequent events accomplishing more geomorphic work than large events should be modified in that this is applicable only to channels in certain climatic and physiographic environments. Smaller and semi-arid catchments with a highly varied flow regime, have high potential for catastrophic response. These were often related to physical variables within the catchment. Pizzuto (1986) holds the view that rare floods determine the morphology of streams in arid and semi-arid environments, with channel depth increasing with increasing flow variability. Recovery from extreme events in semi-arid areas requires a longer time span than humid areas, emphasizing the geomorphic importance of extreme events in these regions (Harvey, 1987).

Wolman and Gerson (1978) pointed out that recovery from catastrophic events in semi-arid regions depends on the growth of vegetation as determined by climate and may be in the order of decades. In semi-arid environments geomorphic processes may be characterised by long periods of inactivity before important events occur (Church, 1980).

In semi-arid environments river channels are adjusted to the larger floods primarily because these flows are often the only flows capable of altering channel morphology and pattern (Kochel, 1988). Thresholds are exceeded in large floods that are not passed by low magnitude events, regardless of their frequency of occurrence.

It would appear that some environments then, are more predisposed to long lasting important geomorphic changes as a result of extreme events than others (Lewin, 1989). The persistence of form in semi-arid environments appear to be in contrast with the rapid recovery of landforms (rivers) following rare events by frequent low magnitude events in humid regions.

2.4 SEDIMENT REGIME

Ferguson (1987) has stated that it may be possible to replace slope or discharge variables with sedimentary variables to predict channel pattern through statistical or graphical means. Spatial and temporal variations in sediment load have important implications for channel pattern. If the sediment load supplied from the catchment exceeds transport capacity, braiding will occur. Carson (1984) has shown that meandering occurs where sediment load is low in relation to stream power, and braiding occurs where both sediment load and stream power are high. Braiding is seen by many researchers (Leopold and Wolman, 1957; Kellerhals, 1982) as a disequilibrium condition in response to aggradation.

Changes in sediment supply may be a response to climatic change, major floods or land-use (Ferguson, 1987). If transient, these may cause sediment slugs or pulses to move through the system, marked by sedimentation zones in which channel form and pattern changes are commonly observed (Church and Jones, 1982; Church, 1983). Storm induced sediment injections and resultant pulses in sediment transport are difficult to integrate with commonly experienced sediment transport regimes (Carling, 1988b).

Sediment supply events tend to be episodic in upland streams and not uniform in their spatial distribution (Simons and Simons, 1987) - the jerky conveyer belt concept suggested by Ferguson (1981). A high rate of coarse sediment input leads to unstable braided channels (Harvey, 1987; Carling, 1988b). Episodic flooding may enable a stream to jump the threshold into a braided regime, or prepare a landform for modification by a succeeding event (Newson, 1980). Thus storm events may often bring about a condition of in-channel sediment availability, as was found for the Roaring river in the United States (Pitlick and Thorne, 1987). This has led to the concept that much of the material derived from upland areas is stored in the channel downstream (Newson and Leeks, 1987) and therefore relationships must exist between long-term bed material transport and systematic channel processes (Neill, 1987). Temporal and spatial channel storages are therefore important determinants of potential channel form and pattern.

Carson (1984) has stated that sediment supply may be the most important control of channel pattern especially for gravel- and cobble-bed channels. Harvey (1991) found that high rates of sediment supply from gulleys and erosion scars have had important effects on streams in the Howgill Fells in Northwest England. A major flood injecting sediment directly to the stream channel was able to kick a relatively stable geomorphic system over the threshold resulting in channel change and instability.

Although it is important to understand the spatial and temporal movement of sediment in channels, this is exceedingly difficult to do (Knighton, 1987) as sediment movement patterns are complicated by storage and transport rates which can vary markedly over distances of less than a kilometre. Generally bedload transport is only dominant in headwater areas, with the transition of a gravel to a sand-bed stream occurring around the D_{50} 10 mm mark (Howard, 1980; Kellerhals, 1982), a discontinuity which has important implications for channel form and pattern adjustment.

2.5 HUMAN IMPACTS ON FLUVIAL SYSTEMS

Park (1981), reviewed man's affect on fluvial systems and showed how man can affect changes in drainage basin processes (magnitude and frequency of events and sediment production) and how this can be transferred into changes in channel form (pattern and geometry). Hooke and Redmond (1989b) have shown that nearly 35% of all rivers in upland England have shown channel instability due mainly to anthropogenic influences through reservoir construction, urbanization and land-use. These factors have directly affected the discharge and sediment regimes of the channels, altering channel form.

The main difference between channel adjustments caused by man's influence and natural adjustment is one of time scale (Simon, 1988), with man induced instability producing rapid changes. Man's influence on river channels is receiving more attention (Park, 1977; Paris, 1984), especially as land management has important effects on the runoff process (Newson and Robinson, 1983) through catchment land-use and management.

The effects of man on river channels can be divided into direct and indirect channel change. Direct change refers to the purposeful human action of modifying channels. These are generally related to engineering schemes such as canalization. Indirect effects relate to human activities such as changes in catchment land-use, overgrazing and so on, that control stream channel and network form (Park, 1981).

Human interference in catchment processes not only affects the character of the flood hydrograph and sediment yields as influenced by land-use (Hickin, 1983; McEwan, 1989), but also affects local stream ecology (Walker, 1985; Carling, 1987). As the aforementioned review has shown, channel size and form is largely a product of the sediment and hydraulic regime, it is therefore logical that land-use disturbance will promote channel change.

Finlayson and Brizga (1990) have indicated that many causes of channel instability in Australia have been identified as human interference primarily through altering hydraulic regime. Erskine (1986) emphasised that channel instability is indicative of a change in energy input. Changes in the Macdonald river in Australia (reduced sinuosity, channel widening, aggradation and increased form ratio) have been ascribed in part to burning and land management practices resulting in increased sediment yields following European occupation. Post 1949 changes have been ascribed to increased annual and summer rainfall totals resulting in a shift in the hydraulic regime.

Warner (1987) has shown that in the Bellinger river, Australia, channel instability was related to large floods, and intensive dairy farming on hillslopes with resultant hydrological consequences. Later detailed work showed that a shift in climatic regime changed the sediment and hydraulic regime of the area. Hydrological consequences of land-use change were thus superimposed on a shift in climate. Increased summer rainfall totals increased runoff and sediment production rates, as well as flood peaks and magnitudes, resulting in channel change.

The channel of the Gila river in Arizona (Burkham, 1972) was stable between 1846 and 1904, whereafter, between 1904 and 1917, major floodplain destruction occurred, with channel width increasing from an average of 150 feet to over 2000 feet. This was thought to be the result of overgrazing affecting catchment hydraulic and sediment regimes, attenuating flood peaks.

Clifton (1989) has shown that grazing management has important influences on catchment and riparian vegetation communities. Grazing in the riparian zone in a second order intermontane stream, the Wickiup Creek, resulted in increased channel bank instability, channel slope adjustments and changes in discharge. Bank vegetation recovery following the exclusion from grazing, resulted in a narrow deep channel, where previously, a wide shallow channel existed.

Other important human induced effects on river channels include: channel aggradation following the injection of mining waste (Durham, 1948; Knighton, 1989), increased bank erosion, channel straightening, upstream degradation and downstream aggradation caused by river engineering works (Erskine, 1990). Reservoir construction leads to regulated flow regimes often accompanied by downstream aggradation (Petts, 1979 and 1985). Clearly man's influence exerts an important influence on all variables controlling channel form and pattern. Any study on channel instability should as a matter of course determine the extent to which man may be responsible for its cause. It should be stated in conclusion that each river system is unique (Carling, 1988b) with different form and processes operating at different temporal and spatial scales.

2.6 CONCLUSION

All factors, flow strength, bank strength, competence, capacity and sediment volume and calibre are involved in the development of non-straight channels. Rivers show gradual transition in pattern rather than sudden changes, patterns also vary over time, mainly because of the variable magnitude and frequency of floods (Ferguson, 1987) but also because of human intervention in drainage basin and channel processes (Park, 1981).

River channel studies are complex and therefore require a variety of different spatial and temporal control variables to be taken into account when attempting to determine cause and effect relationships, channel pattern, form and change. These factors are to be considered in an attempt to determine the cause of channel change in the Bell river. Chapter 4 will examine the local spatial control variables affecting channel form and pattern (bank and bed material and so on), while Chapter 5 (climatic change) and 6 (temporal changes in sediment availability) will look at the temporal control variables affecting potential form and pattern in the Bell river. These will be considered within the framework of contemporary theory.

CHAPTER 3

RESEARCH DESIGN

3.1 INTRODUCTION

The theoretical review (Chapter 2) identified two major groups of factors responsible for determining potential channel form and pattern instability, namely local spatial control variables (channel perimeter material, riparian vegetation, slope and valley gradient) and temporal control variables (discharge and sediment regime). It was therefore necessary to adopt a research framework that would enable the most efficient, objective and cost effective method of obtaining data that would identify spatial and temporal controls of channel form and pattern in the Bell river.

The major problem in geomorphological studies in South Africa is the lack of readily available data. Warner (1987) makes the point that channel change studies are dependent on earlier investigations of channel dimensions and locations. The simple lack of any baseline data in South Africa, be it historical maps, ordinal survey data, or even channel discharge and sediment data is a major limiting factor in process studies. This appears to be in contrast to Europe for example, where Hooke and Redmond (1989a, 1989b) have indicated the comparative wealth of baseline data for channel change studies. In general, when studying channel change in South Africa it is necessary to make use of surrogate data which is generally less satisfactory, but is often all that is available.

Given the data limitations, a methodological approach was designed that attempted to make best use of the available data. The following discussion will therefore focus on the overall research framework adopted to determine the spatial and temporal controls on channel form and pattern in the Bell river.

3.2 SPATIAL CONTROL VARIABLES

Channel change inherently implies a change in channel form, pattern and geometry. It was therefore necessary to determine which spatial control variables affect the potential for channel instability, both at-a-station and downstream. Measurements of channel spatial controls (as identified by contemporary literature) such as bed material characteristics, channel and valley slope, channel perimeter material and channel vegetation were taken. The method used depended on the type of data required and varied according to guidelines suggested by the literature (Wolman, 1954; British Standards Institute (BSI), 1975 for example). Attempts to monitor spatial changes were undertaken through fixed point cross-sectional surveys. During the period of research however, no significant flows of even moderate magnitudes occurred and therefore no significant channel modifications were observed. Coincidence of the research with a drought was not helpful in terms of monitoring short term channel change, but was helpful during manual bed material sampling. This further emphasizes one of the problems of process studies, especially in semi-arid and mountainous areas with varied and flashy hydrological regimes.

3.3 TEMPORAL CONTROL VARIABLES

One of the major problems in process studies are time constraints. As has been mentioned in the theoretical review (Chapter 2), events responsible for geomorphological changes are unpredictable, this is especially so in the Bell river where flood events of at least moderate magnitudes are required to produce measurable channel change. The short time span over which the research is undertaken was also a limiting factor.

The two major temporal control factors identified in the theoretical review as being potentially responsible for change are channel discharge and sediment regime. In an ideal situation, temporal discharge and sediment load changes are measured directly through weirs, flumes, bedload traps, mechanical sediment sampling processes and so on. None of this data is available for the Bell river, however, as sediment load and discharge play such an important role in channel processes (Knighton, 1987, Simon, 1988), surrogate measurements were necessary.

Variations in discharge and sediment regime are predominantly a response to altered catchment processes. Surrogate methods for discharge have been used by other authors; Harvey (1987 and 1991) has used drainage area as a substitute for discharge in correlations with channel form variables. Erskine (1986) used rainfall to show that temporal rainfall variations induced an upward shift in the annual series flood-frequency curve for the Macdonald river in Australia. This, combined with increased catchment erosion was responsible for channel instability. Rainfall records were therefore used as a surrogate for discharge, as it was assumed that temporal variations in discharge would mirror those of rainfall. Furthermore, temporal rainfall variations have significant effects on catchment processes (Harvey, 1991) and can therefore affect channel processes.

The use of sequential soil erosion mapping gives an indication of catchment sediment production and therefore the amount of material available to the channel. Results from sequential soil erosion mapping were therefore used as a surrogate for temporal channel sediment measurements. It was assumed that if sediment production had increased, decreased or remained constant in the catchment that sediment production to the channel would reflect this change. Erskine (1986); Knighton (1989) and Harvey (1991) have all used similar methods to show how channels can adjust to temporal variations in sediment supply from catchments.

3.4 TEMPORAL CONTEXT OF RESEARCH AND DESIGN LIMITATIONS

As was discussed in the Introduction (Chapter 1), the temporal context of the research is important as the distinction of cause and effect relationships is a function of time scale (Schumm and Lichty, 1965). The temporal scale of the research for this study was defined in the context of modern time (0-100 years, Schumm and Lichty's (1965) classification). In this temporal context, river adjustment is considered to be to the dominant discharge and sediment regime.

3.5 CONCLUSION

The above discussion has attempted to show the overall research design adopted and the reasons for the design path. The discussion has also attempted to illuminate the overall research problems encountered, especially the lack of data and how these problems were resolved. Although salient data was not always available and therefore limited research, logistical problems such as distance of the catchment from the University (500 km) and the size of the catchment (424 square kilometres) also proved to be limiting factors. The research design adopted attempted to overcome the data limitations, but these limitations effectively determined the research path and therefore determined what could be achieved.

CHAPTER 4

SPATIAL CONTROL VARIABLES IN THE BELL RIVER CHANNEL

4.1 INTRODUCTION

Channel instability has occurred in the Bell river in the form of meander cutoffs, incipient meander cutoffs and general channel instability (Chapter 1). In Chapter 2 it was demonstrated that channel changes can be caused by two major groups of factors, autogenic and allogenic. It was also pointed out in Chapter 2 that variables other than discharge can affect channel form (sediment load for example); these variables (channel perimeter material, bank vegetation, bankfull discharge and channel bed material) will be examined in order to assess their impact on the Bell river. Spatial control variables, which determine bed and bank stability, determine the nature and direction of channel adjustment, while catchment controls, which determine water and sediment discharge (see Chapter 5 and 6), initiate or trigger channel instability and change.

4.2 KEY QUESTIONS

The main question to be addressed in this Chapter is whether or not the Bell river is unstable or in disequilibrium. Meander cutoffs, incipient meander cutoffs, channel widening and general channel instability exists in the Bell river. This may, however, form part of the natural cycle of the river, rather than being related to changes in external factors such as discharge and sediment load. In order to determine whether the channel is truly unstable, it is necessary to determine:

a) What factors determine channel form and if these are related in any way to possible changes in external factors?, and

b) If the river is unstable what local factors determine where instability takes place?

If the channel is in equilibrium, then the following should apply:

- Consistent channel form relationships (see Chapter 2)
- Longitudinal increase in channel form dimensions
- Longitudinal reductions in sediment calibre
- Longitudinal increase in bankfull discharge
- Channel-pattern discharge relationships.

If these do not apply, then it can be concluded that the channel is probably in disequilibrium, indicating that within the context of modern time, external factors must be responsible for channel instability.

In this context the key questions that need to be addressed are:

a) What is the spatial variability of channel pattern and form?
b) What is the spatial variation of control variables determining channel pattern and form?
c) What is the relationship between channel form and channel control variables?, and
d) What is the relationship between thresholds for channel pattern change and control variables?

4.3 AIMS AND OBJECTIVES

4.3.1 Aim

The major aim of the research presented in this Chapter is to determine the spatial controls in the Bell river that may be responsible for the type, nature and direction of channel form and pattern adjustment in order to assess whether the Bell river is truly unstable.

4.3.2 Objectives

The general objectives of the research are to determine at selected sites:

a) Field measurements of channel form and control variables
b) Hypothesis testing of channel form relationships, and
c) Analysis of pattern and threshold relationships.

In order to achieve these the following specific objectives have been identified, namely to determine:

a) Channel pattern.

b) Channel form including: width, depth, cross-sectional area, width-depth ratio and channel gradient.

c) Estimated bankfull discharge.

d) Valley gradient.

e) Bed material characteristics, including clast size, sorting coefficient and asymmetry indices along the channel.

f) Channel perimeter material.

g) Channel bank vegetation characteristics.

h) Channel pattern and threshold limits.

4.4 METHODOLOGY

A seventeen kilometre stretch of channel was identified for analysis which included those reaches which showed evidence of recent channel instability. Seventeen sites at approximately 1 kilometre intervals were selected for analysis of bed and bank material and general channel form.

A further subsection of 10 sites was selected for detailed surveys of channel cross-section, geometry, gradient, estimated bankfull discharge, and bank vegetation characteristics. This choice of a sub-section of sites was due mainly to logistical constraints, in particular, access to the site. sites with a large bedrock component in the bank or bed were excluded. The location of these sites is indicated in Figure 4.1.

4.4.1 CHANNEL PATTERN DETERMINATION

For each of the seventeen sections surveyed, sketch maps were drawn (see Appendix B) and details of planform and degree of instability were observed. This aided the identification of unstable sections. Sinuosity Indices (SI's) were calculated for the entire channel reach for sites 1 to 17 for the dates 1952, 1969, 1975 and 1991, as well as for different sections 1-5, 6-9, 10-13 and 14-17. These sections were chosen as they represented major breaks of slope. SI's were calculated from aerial photographs and 1:50 000 topographical maps. Brice (1964) defined channel pattern in terms of sinuosity index expressed as:

$$SI = \frac{\text{Thalweg Length}}{\text{Meander Belt Axis}} \quad \text{... (Eq. 4.1)}$$

Where: SI < 1.05 is a straight channel
SI 1.05 - 1.5 is a sinuous channel, and
SI > 1.5 is a meandering channel

Sinuosity as predicted by Schumm's (1960) equation was calculated for the Bell river for the study reach as:

$$P \text{ (Sinuosity)} = 0.94\, M^{0.25} \quad \text{... (Eq. 4.2)}$$

Where: M is the weighted silt-clay percentage (see Eq. 4.8) in the channel perimeter

4.4.2 CHANNEL FORM MEASUREMENTS

Cross-sections were surveyed using a surveyor's level at 10 sites: 1, 4, 6, 7, 8, 10, 12, 14, 15 and 17 (see Appendix C). From these cross-sections, width, depth and width-depth ratios were determined. At two (1 and 8) of the sites, more than one cross-section was surveyed, as these sites displayed a change in cross-sectional form over the 100 metre reach (note that at the other cross-sections, form was relatively uniform along the length of the reach). Results from these two sections are the averages of the surveys.

Channel floor gradient was measured using surveyors' equipment. Gradient measurements were taken in the channel from the upstream section of each surveyed site to the downstream end point. Due to the existence of pool and riffle sequences, the gradient reading was taken as the regression slope of height on distance.

4.4.3 CHANNEL CONTROL VARIABLES

4.4.3.1 Estimation of Bankfull Discharge

From the cross-sections bankfull velocity was calculated using Manning's equation (Barnes, 1967; Dunne and Leopold, 1978):

$$V = \frac{R^{2/3} \cdot S^{1/2}}{n} \quad \text{... (Eq. 4.3)}$$

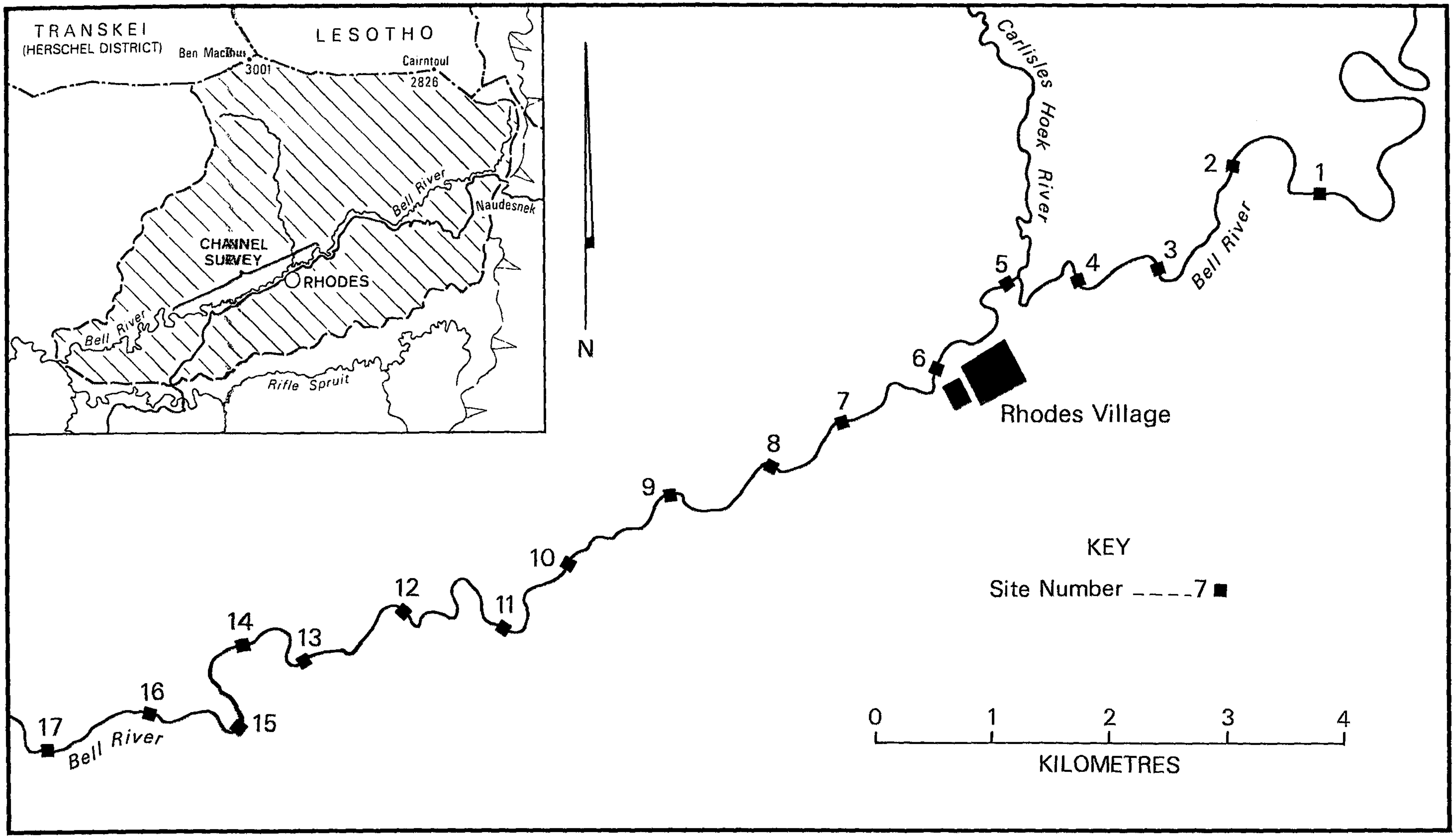
Where: V is velocity in metres per second
R is the hydraulic radius (approximately mean depth)
S is the energy gradient (approximately channel slope)
n is Manning's roughness coefficient

This enabled the determination of bankfull discharge (Q_b) expressed as:

$$Q_b = A.V \quad \text{... (Eq. 4.4)}$$

Where: A is cross-sectional area,
V is velocity

Figure 4.1: Location of Study Sites, Bell River



Errors in the estimation of Manning's n and water surface slope means that bankfull discharge estimates can only be approximations. Discharge has been thought to be closely correlated to drainage area. A quantitative measure of discharge can be made, with the understanding that high degree of error may exist in the results. It is known that discharge does not increase as quickly as drainage area (Dunne and Leopold, 1978), and can be expressed by the equation:

$$Q_f = CD_a^N \text{ ... (Eq. 4.5)}$$

Where: Q_f is the discharge for a flood at a given frequency
D_a is the drainage area
C is the coefficient that depends on climate and frequency of floods, and
N is an exponent less the unity, often between 0.7 and 0.8 (Dunne and Leopold, 1978).

Using equation 4.5, an index was obtained whereby an estimate can be made of the extent to which bankfull discharge should increase longitudinally given an increasing drainage area. It should be stressed that Equation 4.5 was used only to express the relative increase in discharge that should accompany increasing drainage area. The exponent N used to complete the expression was calculated for 2 values, 0.7 and 0.8, ensuring a margin of variability. Results are averages of the two values. Drainage area for each site was calculated using a Geographical Information System (GIS) (pc ARCINFO).

4.4.3.2 Valley Gradient

Valley gradient was calculated for the entire stream length of the Bell river. Valley gradient was also calculated for four different reaches for the study stretch. Gradients were calculated from 1:50 000 topographical sheets. These reaches were identified as the gradients between reaches 1-5, 6-9, 10-13 and 14-17. These reaches were used to retain consistency, as sinuosity indices were also calculated for the same reaches (see 4.4.1).

4.4.3.3 Survey Method: Bed Material Sampling

At each of the 17 sites, channel bed material was sampled. The problem of obtaining an accurate, reliable and representative sample of bed material has been stressed by many authors (Wolman, 1954; Church *et al*, 1987). This is due mainly to the wide range of clast sizes, as well as other problems such as the determination of sample size, surface armouring and imbrication, which tend to hide the finer underlying material (Hey and Thorne, 1983; Hassan, 1990; Mangelsdorf *et al*, 1990). Temporal changes in the size of bed material make accurate sampling difficult as Hubbell (1987) has noted.

Many authors have suggested different methods for sampling bed material including: surface clast counts, surface and subsurface bulking and sieving (Ferguson and Ashworth, 1991), surface counts using a grid system (Wolman, 1954), pacing (Mosley and Tindale, 1985) and transect sampling (Kellerhals and Bray, 1971; Ibheken, 1974). Bed material sampling techniques differ and are adapted to the objectives of the survey and to financial and technological constraints.

Of importance in bed material sampling is the level of accuracy required. Spatial sediment variability in a stream means that a sample taken at one location will not be a true reflection of the entire bed. The problem is to determine the quantity of samples required to provide a representative sample of the whole bed. Mosley and Tindale (1985) suggest that 70 samples per site is necessary. Wolman (1954) and Brusch (1961) suggested that a sample of 60 is adequate. Although it is widely held that increasing sample size produces more accurate results, Mosley and Tindale (1985) found that for surface samples, an increase in the level of accuracy requires a substantial increase in sample size.

Based on previous experience by other authors, as well as resource constraints, it was decided to use a combination of surface clast counts and bulk subsurface sampling and sieving. At each site for mixed bed material (cobbles/sand/gravel), 100 points were sampled at 5 metre intervals along a zig zag line. At each point, a sample was taken, being the first stone touched with the index finger. The median axis of the clast was measured using a calliper.

If sand/fine gravel was encountered, then a note S was made and at the first and thereafter every fifth point, sand was sampled using a trowel. This enabled a sample to be taken to a depth of about 20 centimetres. If the reach was entirely sand/gravel material, 15 samples were taken using the sample procedure as stated above.

In the laboratory, the fine bed material for each site was bulked, weighed and sieved, using a variety of mesh sizes to determine different clast sizes. All analyses were replicated to ensure reliable, accurate results.

4.4.3.4 Bed Material Analysis

A cumulative curve was drawn up from the results obtained for each site (see Appendix D), by combining the results for the coarse and fine particles. From these curves it was possible to determine grain sizes at different percentiles. Values for D_{25}, D_{50} and D_{75} were extracted from the graph and used to determine sorting and asymmetry indices (Mangelsdorf *et al*, 1990; Jiongxin, 1991).

The sorting coefficient (S_o) is defined as:

$$S_o = (\sqrt{D_{75}/D_{25}}) \quad \text{... (Eq. 4.6)}$$

Where: D_{25} and D_{75} are the percentiles at which 25 and 75 percent of the bed material are finer.

S_o is always > 1, the larger the value, the more poorly the sediment is sorted. Rivers with poorly sorted material are believed to indicate a high degree of flow variability, whereas rivers with well sorted materials indicate a consistent flow pattern (Jiongxin, 1991).

The asymmetry index determines which grain size is dominant in the sample (Jiongxin, 1991). The asymmetry index is defined as:

$$S_k = (D_{75}.D_{25})/D_{50}^2 \text{ ... (Eq. 4.7)}$$

Where: S_k is the asymmetry index

D_{50} is the median grain size

If $S_k > 1$, then the fine grained sediment dominates, if $S_k < 1$, the coarse grained sediment dominates. The equation serves effectively as a skewness index.

4.4.3.5 Channel Perimeter Material

Sediment samples were taken from the banks at each site (1-17), representing approximately 100 metres of channel. Samples were taken at 30 metre intervals from both banks, from each distinct horizon. Particle size was determined using the hydrometer method, which is a standard method for particle size analysis based on the settling velocity of particles in a liquid medium (British Standards Institute (BSI), 1975; Briggs, 1977; Carver, 1982; Klute, 1986). From the results of the hydrometer analysis it was possible to determine the percentage sand, silt and clay in the channel banks for each site. Samples were duplicated to ensure accuracy.

A weighted mean percent silt-clay index (M) was calculated (Schumm, 1960). The equation is expressed as:

$$M = \frac{Sc.W+Sb.2D}{W+2D} \text{ ... (Eq. 4.8)}$$

Where: Sc is the percentage silt-clay in the channel alluvium

Sb is the percentage silt-clay in the bank material

D is the average channel depth

W is the channel width

4.4.3.6 Channel Vegetation Characteristics

In order to assess the effects of channel vegetation on bank stability, a classification system based on that of Thorne (1990) was used. At each site (1, 4, 6, 7, 8, 10, 12, 14, 15 and 17) vegetation was ranked according to it's assumed effect on bank stability. Dominant species at each site were also identified. The classification system is presented in Table 4.1. Having assessed the effect of riparian vegetation on bank stability, each site was categorized as a site with either high, medium or low vegetation densities.

Table 4.1: Vegetation Classification according to Thorne (1990)

TYPE	DENSITY	POSITION
Grasses	Sparse	Bank Toe
Shrubs	Open	Mid-Bank
Trees	Dense	Top Bank
DIVERSITY	**AGE**	**SPACING**
Mono-stand	Immature	Continuous
Mixed	Mature	Close
Climax-vegetation	Old	Wide
HEALTH	**HEIGHT**	**EXTENT**
Healthy	Short	Wide
Fair	Medium	Medium
Poor	Tall	Narrow

4.4.4 RELATIONSHIP BETWEEN CHANNEL FORM AND CHANNEL CONTROL VARIABLES

In order to test the existence, strength and nature of the relationship between channel form and control variables (see Table 4.2 for list), hypotheses were set up and tested using both parametric and non-parametric tests.

The Null hypothesis stated: There is no significant relationship between channel form A and channel control A at the 0.05 level of significance.

The Alternate hypothesis stated: There is a significant relationship between channel form A and channel control A at the 0.05 level of significance.

To test for the relationship between drainage area and longitudinal spatial variation in channel form and control variables (see Table 4.2 for list) the following hypotheses were tested:

The Null hypothesis stated: There is no significant relationship between Variable A and Drainage Area at the

0.05 level of significance.

The Alternate hypothesis stated: There is a significant relationship between Variable A and Drainage Area A at the 0.05 level of significance.

Table 4.2: Variables Tested for Relationship Between Channel Form and Channel Control Variables

CHANNEL FORM VARIABLES	CHANNEL CONTROL VARIABLES
Width	D_{25}
Depth	D_{50}
Cross-sectional Area	D_{75}
Form Ratio	S_o
	S_k
	Gradient
	Bankfull Discharge
	Silt-Clay Ratio

4.5 RESULTS

The results will be presented and discussed in the order of the key questions identified (see 4.2), these were:

a) The spatial variability of channel pattern and form
b) The spatial variation of control variables determining channel pattern and form
c) The relationship between channel form and channel control variables, and
d) The relationship between thresholds for channel pattern change and control variables.

4.5.1 SPATIAL VARIABILITY OF CHANNEL FORM AND PATTERN

4.5.1.1 Channel Pattern

From field evidence and sketch maps (Appendix B) channel type and stability were estimated. The results of this analysis are presented in Table 4.3. This aided the identification of unstable channel reaches. The upper sites of the river (1-7) tend to have larger sediment sizes and ranges (see Figure 4.2), while the lower sites (8-17) show smaller sediment sizes and a narrower range of size. Sites with higher vegetation densities tend to be meandering single channels and are generally stable at flows less than bankfull. The upper sites are subject to active channel shifting rather than true channel avulsion, as was found for a number of the lower sites. The major incidences of channel instability have been identified at the transitional zone between the upper reaches and the lower reaches. This will be explained later in terms of the transitional zones identified by Warner (1987).

Table 4.3: Channel Characteristics, Bell River

SITE NUMBER	SINUOSITY	CHANNEL TYPE	COMMENT
1	Meandering	Single	Upstream of Divided Reach, with Abandoned Channels
2	Straight	Single	Partially Controlled Bedrock Channel
3	Meandering	Divided	
4	Meandering	Single	High Riparian Vegetation
5	Meandering	Single	Immediately Below Tributary Junction
6	Straight	Single	Stable Section, Tributary Sediment Injection
7	Straight	Divided	Recent Instability, Meander Cutoffs, Channel Instability
8	Straight	Single	Channel Widening Immediately Downstream From Meander Cutoff
9	Straight	Divided	Meander Cutoff
10	Meandering	Single	Downstream of Divided Reach, Tributary Sediment Injection
11	Meandering	Single	
12	Meandering	Single	Tree Planting to Inhibit Bank Widening
13	Straight	Single	Semi-Controlled Bedrock Bank
14	Straight	Single	Upstream of Meander Cutoff
15	Meandering	Single	High Riparian Vegetation, Over Bank Flows Resulting in Behind Bank Incision
16	Straight	Single	Partially Hillslope Controlled
17	Meandering	Single	Downstream of Tributary Injection of Coarse Material

Sinuosity Indices calculated using Brice's (1964) classification were determined for selected reaches for the years 1952, 1969, 1975 and 1991 (Table 4.4). The results indicate that sinuosity has decreased in the Bell river since 1952 with attendant channel straightening. Although the upper sites (1-4 and 5-7) do show sinuosity reductions, the lower sites (8-11 and 12-17) indicate a relatively greater reduction in sinuosity. Predicted sinuosity for the entire reach of the Bell river using an empirical equation from Schumm (1960) (see Equation 4.2) is 1.41, which indicates a sinuous channel (Brice's, 1964 classification). This is higher than the present day sinuosity (P = 1.36), but lower than the sinuosity calculated for 1952 (P = 1.51). The channel is clearly in a state of adjustment, indicated by sinuosity reductions with attendant channel straightening.

Table 4.4: Bell River, Sinuosity Index (Equation 4.1)

REACH NUMBER	1952	1969	1975	1991
1-4	1.40	1.40	1.39	1.39
5-7	1.49	1.47	1.44	1.42
8-11	1.40	1.35	1.28	1.26
12-17	1.71	1.68	1.65	1.64
1-17	1.51	1.48	1.38	1.36

4.5.1.2 Channel Form

Width, depth, cross-sectional area, width-depth ratio, reach gradient and estimated bankfull discharge were calculated from the survey data for the subsection of 10 sites. A selected display of the data are presented in Figure 4.2. and Table 4.5.

Width, depth, width-depth ratio and cross-sectional area display similar characteristics evidenced by no consistent longitudinal change. Width, depth, cross-sectional area, form ratio and gradient do however, show considerable variation in the range of values. What is apparent is that the upper reaches (sites 1-7) show high variability in width and form ratio, while the lower sections (sites 8-17) display a narrower range of values.

4.5.2 SPATIAL VARIABILITY OF CHANNEL CONTROL VARIABLES

4.5.2.1 Discharge

As mentioned in Chapter 3, no flow data was available to monitor discharge in the Bell river. However, the results from Equation 4.5 would suggest that discharge should increase between site 1 and site 17, as the drainage area increases from 221km^2 to 328km^2 (Table 4.5). Almost half of this increase (17-20%) occurs between site 4 and 5 with the injection of flow from the Carlisle's Hoek tributary (see Figure 4.1). If discharge increases at approximately 0.7 to 0.8 power of area (Dunne and Leopold, 1978), an increase of between 35 to 41% would be expected. This should have no significant effect on channel form.

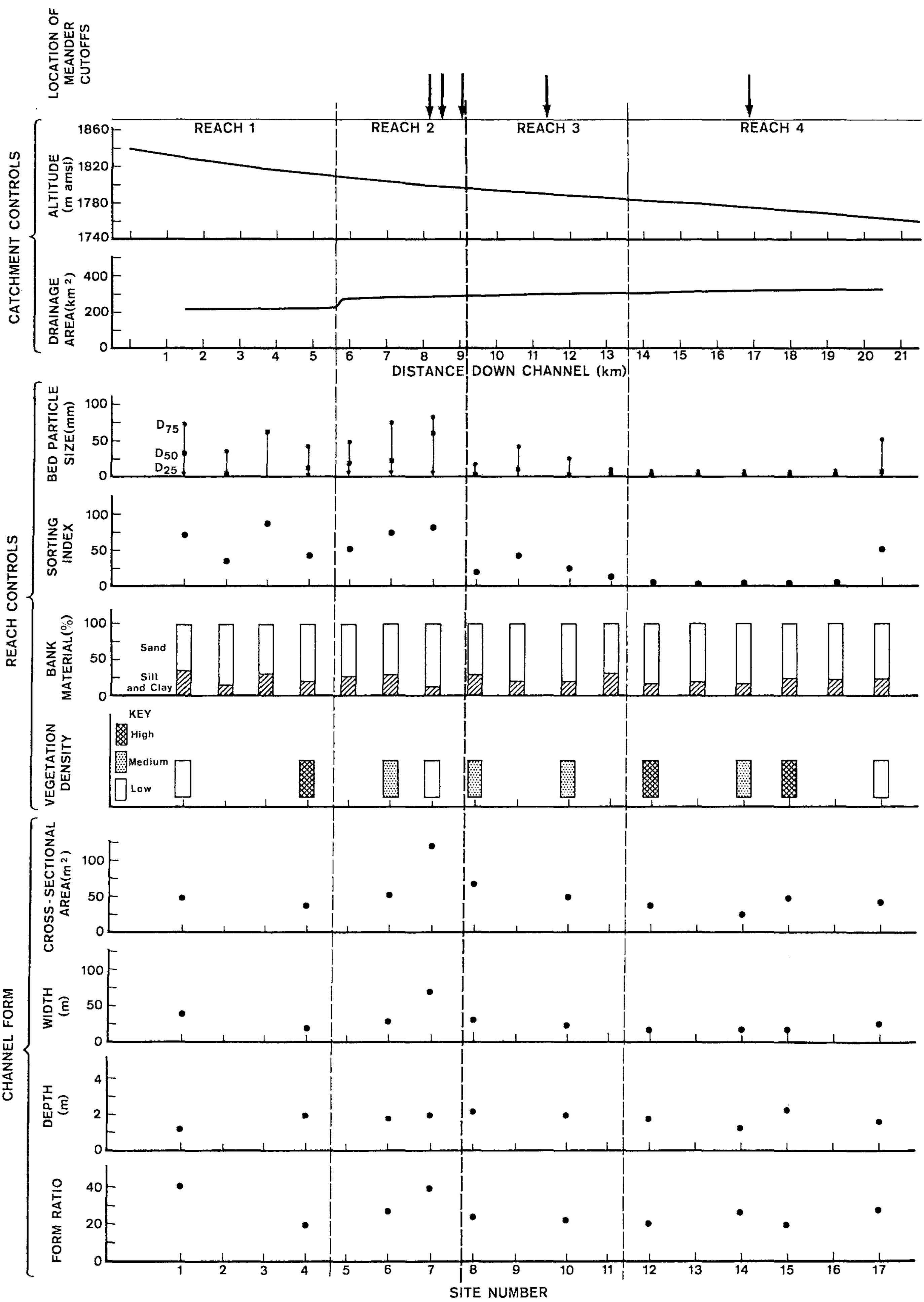
Results (Table 4.5) from the estimation of bankfull discharge using Manning's n, indicate a range of 22m^{3}sec^{-1} (site 14) to 407m^{3}sec^{-1} (site 7) along the 17 km stretch. The tremendous variability shown by the results suggests that factors other than discharge are the major controlling factors of channel form. This means that some streams are underfit (site 7), while some (sites 14 and 15) have a greater potential for flooding given the reduced capacity.

The median value calculated for bankfull discharge (90 m^{3}sec^{-1}) is supported by the flood-frequency analysis undertaken for the Kraai river (see Chapter 5). This value was therefore used as the bankfull discharge estimate in the empirical equations and was applied longitudinally to all reaches.

Table 4.5: Channel Control and Form Variables, Bell River

Site Number	Drainage Area (km^2)	D_{25}	D_{50}	D_{75}	S_o	S_k	Width (m)	Depth (m)	Cross-sectional Area	Form Ratio	Gradient	Q_b (cumecs)	Weighted Silt-Clay	Silt-Clay %
1	221	0.59	30.00	70	10.89	0.05	38.75	1.26	48.83	31.36	0.0080	128.41	2.18	34.20
2		0.52	0.83	34	8.09	25.66								15.00
3		1.80	62.00	84	6.83	0.04								32.00
4	229	0.56	12.00	41	8.65	0.16	19.52	1.98	38.65	9.88	0.0060	152.67	4.67	20.27
5	287	0.58	18.00	48	9.10	0.09								27.00
6	290	5.00	22.00	74	3.85	0.76	30.00	1.76	52.80	17.04	0.0010	62.30	5.10	29.71
7		4.00	59.00	82	4.53	0.09	60.00	1.97	122.25	30.46	0.0070	407.09	13.70	13.50
8	294	0.52	0.59	17	5.72	25.40	30.96	2.19	67.80	14.03	0.0010	95.60	5.46	29.82
9		0.58	10.00	41	8.41	0.24								21.00
10	301	0.56	2.10	25	6.68	3.17	25.24	1.97	49.72	12.81	0.0020	82.54	2.84	21.00
11		0.56	1.20	10	4.27	3.97								32.00
12	307	0.54	0.59	03	2.28	4.34	19.52	1.91	37.28	10.22	0.0040	95.82	3.71	17.00
13		0.28	0.57	01	1.45	0.51								19.00
14	320	0.50	0.61	03	2.32	3.63	19.52	1.20	23.42	16.27	0.0009	22.02	2.33	17.40
15	321	0.51	0.59	03	2.21	3.66	21.43	2.25	48.22	9.52	0.0005	32.31	7.11	24.89
16		0.58	1.40	04	2.56	1.12								23.00
17	328	0.51	6.90	49	9.80	0.52	27.14	1.55	42.07	17.51	0.0040	90.86	2.91	24.00

Figure 4.2: Controls on Channel Form and Pattern in the Bell River



4.5.2.2 Valley Gradient

Table 4.6 displays the valley gradient calculated for the four reaches. Figure 4.2 shows the valley long profile determined for the study reach. The valley gradient tends to be steeper in the upper reach (1-4) and declines in the next two reaches (5-7 and 8-11). A slight steepening of the gradient in reach 4 (12-17) is noted. These reductions are expected as the channel moves from the headwaters of the catchment into a broader, flatter floodplain area.

Table 4.6: Valley Gradient for the Bell River

REACH NUMBER	VALLEY GRADIENT
1-4	0.0084
5-7	0.0058
8-11	0.0036
12-17	0.0040

4.5.2.3 Channel Bed Material

Table 4.5 displays the results obtained from the survey of the channel bed material. From the analysis of bed material, it was possible to determine the Sorting (S_o) and Asymmetry (S_k) indices. Channel bed material displays considerable variability, both longitudinally and at-a-station. Longitudinal variation exists with general downstream fining and reduced clast size variation at each site. Two distinct groups of sites appear to exist, an upper section (1-7) and a lower section (8-17). The upper section displays larger bed material sizes, a greater range of sediment sizes and poor sorting. The lower section shows smaller bed material sizes with a smaller sediment range and well sorted bed material. This appears to be associated with a transition from a gravel/cobble-bed stream to a mobile sand-bed stream.

This shift has been noted previously by other authors and is associated with a shift in the median grain size (Knighton, 1987), where the bed tends to change from a gravel to a sand-bed stream at approximately 10 mm median grain size. After site 7 the bed shows an abrupt transition from a gravel- to a sand-bed stream (Figure 4.2).

As noted previously, the upper section also shows higher form ratios and steeper channel gradients. The upper section also contrasts with the lower section in that the upper section tends to display channel shifting rather than clear meander cutoffs. Sediment production through channel straightening tends to mobilize finer bank material. This source may account to some extent for the high level of fine material in the lower study reach.

4.5.2.4 Channel Perimeter Material

Results from channel perimeter material sampled are presented in the Table 4.5. The silt-clay percentage for each site is presented graphically in Figure 4.2. Although there is considerable variability of bank material sediment size, no clear downstream trend is apparent. Silt-clay percentages range from nearly 35% in site 1 to 13% in site 7. Site 7 has the highest width and estimated bankfull discharge, but also has the lowest silt-clay ratio. It also has the lowest vegetation density.

4.5.2.5 Channel Vegetation Characteristics

Figure 1.2 presents the channel vegetation for sequential dates for the Bell river as determined through aerial photographs. This figure shows how riparian vegetation has increased consistently since 1952. Although no aerial photographs were available for 1991, field surveys would indicate substantial growth in woody riparian vegetation since 1975. This has been the result of extensive tree planting during the last 30 years by farmers in a effort to combat instability. The main species planted has been identified as *Salix caprea*, an exotic species. Another species *Salix babylonica* has also been introduced to combat bank instability. However, as *S. caprea* is a faster growing tree, and it's rooting extensively binds the soil, this has been preferred by many farmers.

Table 4.7 shows the results obtained for the vegetation classification according to Thorne (1990). The rank of the sites is also presented. Rank 1 refers to that reach where vegetation characteristics are such that they should make a greater contribution to bank stability. It should be noted that although this is a fairly subjective assessment, a degree of objectivity was attained through the use of this classification system.

Table 4.7: Vegetation Characteristics for Selected Reaches, Bell River

SITE NUMBER	1	4	6	7	8	10	12	14	15	17
Type	Trees	Grass and Trees	Grass and Trees	Grasses	Grasses, Shrubs and Trees	Grasses, Trees	Trees	Grasses, Trees	Trees	Grasses, Trees
Diversity	Mixed	Mixed	Mixed	Mixed	Mixed	Mixed	Mixed	Mixed	Mono-Stand	Mono-Stand
Health	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
Density	Sparse	Dense	Open	Sparse	Open	Open	Open	Open	Dense	Sparse
Age	Immat.	Immat. and Mature	Mature	Mature	Mature	Immat. and Mature	Immat.and Mature	Immat. and Mature	Immat. and Mature	Mature
Height	Medium	Tall and Short	Tall	Medium	Tall	Tall and Medium	Tall	Tall	Tall	Tall
Position	Bank Toe	Bank Toe	Bank Toe and Mid Bank	Bank Top	Bank Toe, Mid Bank, Top Bank	Bank Toe, Mid Bank	Bank Toe, Mid Bank, Top Bank	Bank Toe, Mid Bank, Top Bank	Bank Toe Mid Bank	Top Bank
Spacing	Wide	Close	Close	Wide	Wide	Wide	Continuous	Close	Close	Wide
Extent	Medium	Narrow	Medium	Wide	Medium	Medium	Medium	Medium	Medium	Wide
Dominant Species	*S.caprea*	*S.caprea*	*S.caprea*	*S.caprea*	*S.babylonica*	*S.caprea*	*S.caprea*	*S.caprea*	*S.caprea*	*S.caprea* *S.babylonica*
Comment	No RHB Tree Lining	Root Matting Stabilizing Bank	Root Matting Stabilizing Bank	Bank Collapse and Basal Clearance	No Root Matting	LHB Better Vegetated than RHB	Dense Root Matting	Few S.Babylonica	Few S.Babylonica	RHB Mainly Grass Covered
Rank	9	2	5	10	7	6	3	4	1	8
Density	Low	High	Medium	Low	Medium	Medium	High	Medium	High	Low

4.5.3 RELATIONSHIP BETWEEN CHANNEL FORM AND CONTROL VARIABLES

Table 4.8 displays the results obtained from the hypothesis testing. Results indicate acceptance of the alternate hypothesis. D_{50} is correlated to width (r = 0.71) and form ratio (r = 0.77) (Table 4.8). Both these correlations are positive, indicating that sediment material plays an important role in determining channel width and form ratio. Wider channel reaches and larger form ratios are associated with larger bed material, narrower reaches and smaller form ratios are associated with channels with finer material.

Width is also strongly correlated with D_{75} (r = 0.71). This is in contrast to the relationship with smaller bed material (D_{25}) which appears to have no effect on channel form. However, the danger of defining a cause and effect relationship has been identified by many authors (Park, 1981; Knighton, 1987). It may be that bed material calibre is adjusting to width, and that increased widths are reducing flow velocities and competence, inducing deposition. The importance of this observation is not however the cause and effect relationship, but rather the existence and implications of the relationship.

Sorting Index is positively correlated to bankfull discharge and gradient (r = 0.75 and 0.75 respectively). The steeper the gradient and greater the bankfull discharge the more poorly sorted the bed material. Bankfull discharge is also correlated to gradient (r = 0.82), but because of the co-linearity error between estimated bankfull discharge and gradient, this was not taken any further. This is associated with areas of local instability where variable flow velocities are experienced across the reach. This serves as an example of the complexity of river channel response in space and time, in that the recognition of cause and effect may be problematic.

Mean weighted silt-clay percentage is positively correlated to depth (r = 0.81). Higher silt-clay percentages increase bank cohesion, allowing deeper channels. There is no relationship between width and silt-clay percentages (see Table 4.8), indicating that perhaps silt-clay percentages are not sufficient to resist channel widening, but are sufficient to maintain vertical cohesion. This may be related to basal erosion of coarser bank material. As width has been correlated to bed material size, and the evidence presented in this Chapter indicates that the lower reaches have finer bed material, it is possible to suggest that finer bed material is associated with a decrease in width and an increase in depth.

Table 4.8: Correlations for Spatial Control Variables and Channel Form Variables at 0.05 Level of Significance

	DRAINAGE AREA	D_{25}	D_{50}	D_{75}	S_O	S_K	WIDTH	DEPTH	CROSS-SEC.AL AREA	FORM RATIO	GRADIENT	BANKFULL Q	WEIGHTED SILT CLAY
DRAINAGE AREA		-0.1	-0.73	-0.55	-0.61	0.71	-0.42	0.15	-0.13	-0.45	-0.77	-0.78	0.14
D_{25}			0.48	0.57	-0.20	-0.18	0.24	-0.02	0.22	0.10	-0.27	-0.18	0.23
D_{50}				0.90	0.55	-0.42	0.71	-0.45	0.15	0.77	0.60	0.44	-0.22
D_{75}					0.66	-0.37	0.71	-0.36	0.27	0.65	0.48	0.45	-0.22
S_o						-0.18	0.57	-0.28	0.20	0.57	0.75	0.75	-0.43
S_k							0.15	0.44	0.61	-0.19	-0.41	-0.03	0.34
WIDTH								-0.27	0.62	0.83	0.33	0.29	-0.20
DEPTH									0.55	-0.73	-0.37	0.05	0.81
CROSS-SEC.AL AREA										0.09	-0.15	0.21	0.46
FORM RATIO											0.52	0.21	-0.46
GRADIENT												0.82	-0.47
BANKFULL Q													-0.57
WEIGHTED SILT-CLAY													

In order to test for a relationship between vegetation characteristics and form variables (width, form ratio and cross-sectional area), it was necessary to make use of the non-parametric Spearmans Rank correlation coefficient (r_s) used for ordinal (ranked) data. Results indicate acceptance of the alternate hypothesis.

Table 4.9: Correlations for the Relationship Between Vegetation and Channel Form at the 0.05 level of Significance

VARIABLE	CORRELATION COEFFICIENT
Vegetation and Width	-0.85
Vegetation and Form Ratio	-0.89

Results of the Spearmans Rank correlation test have indicated that vegetation is negatively correlated to width (r_s = -0.85) (Table 4.9) and form ratio (r_s = -0.89). This demonstrates that the higher the density of riparian vegetation, the narrower the width and form ratio, the lower the density of vegetation, the wider the width and form ratio. Vegetation density clearly has a significant impact on channel form.

It is suggested that sites with low riparian vegetation density in the Bell river have a greater potential for channel instability. Where vegetation is planted, channels tend to stabilize and narrow. Although vegetation is important in controlling channel form and stabilising the banks, the reduction in cross-sectional form increases the potential for overbank flooding and therefore scouring and possible channel avulsion. Vegetation therefore plays an important role in channel form and pattern in the Bell river and should certainly be considered in predictive equations relating to channel form. Failure to take cognisance of the importance of riparian vegetation in the interpretation channel form may result in an inaccurate assessment of channel control variables.

An attempt to integrate the effect of vegetation with the predicted effect of bank sediment (see Table 4.10 and 4.11) on form ratio using Equation 4.9. was undertaken. Column 5 in Table 4.10 shows the ratio of measured form ratio (Fa) to predicted form ratio (Fp). Table 4.11 shows that where vegetation density has been classified as high, the form ratio is between 0.19 and 0.28 of that predicted using bank material alone, a medium density of bank vegetation is associated with a variable ratio of between 0.31 and 0.63, whereas a low density of bank vegetation is associated with a more variable ratio of 0.43 and 1.36. More variable form ratios are associated with lower vegetation densities and vice versa.

Rowntree and Dollar (1992) have attempted to estimate of the effectiveness of vegetation as an equivalent silt-clay content, where the measured F value (Fa in Table 4.10) was inserted in Equation 4.9 (Richards, 1982) so the equivalent B value could be calculated:

$$F \text{ (Form Ratio)} = 800Q_b^{0.15} B^{-1.20} \text{ ... (Eq. 4.9)}$$

Where: Q_b is bankfull discharge

B is percent of silt-clay in the channel banks

High density vegetation offers, in theory, the equivalent resistance of a silt-clay content of 68%, medium vegetation density the equivalent of 43-54% silt-clay content and low vegetation density an equivalent silt-clay percentage of between 26-41%. Bank vegetation therefore has an important impact on bank stability and therefore channel form. High density vegetation tends to stabilize the channel perimeter. The spatial distribution and density of vegetation would appear to have an important effect on channel bank stability, and therefore channel form.

Table 4.10: Prediction of Form Ratio (F) from Silt-Clay Content (B)

SITE	SILT-CLAY (%)	MEASURED F (Fa)	PREDICTED F (Fp)	Fa/Fp
1	34	31	23	1.36
4	20	10	43	0.23
6	30	17	27	0.63
7	14	30	70	0.43
8	30	14	27	0.52
10	21	13	41	0.31
12	17	10	53	0.19
14	17	16	53	0.31
15	25	10	34	0.28
17	24	18	35	0.50

Table 4.11: The Effect of Bank Vegetation on Channel Form

SITE NUMBER	DENSITY OF BANK VEGETATION	Fa/Fp	EQUIVALENT SILT-CLAY CONTENT %
1, 7, 17	Low	1.36, 0.43, 0.50	26, 27, 41
6, 8, 10, 4	Medium	0.63, 0.52, 0.31, 0.31	43, 51, 46, 54
4, 12, 15	High	0.28, 0.23, 0.19	68, 68, 68

4.5.3.1 Downstream Changes In Channel Form and Control Variables

Longitudinal variations in reach and form variables were tested. Table 4.12 displays the results at the 0.05 level of significance. Results indicate acceptance of the alternate hypothesis.

Table 4.12: Correlations for Longitudinal Changes in Channel Form and Control Variables at the 0.05 level of Significance

VARIABLE	CORRELATION COEFFICIENT
Drainage Area and D_{50}	-0.73
Drainage Area and Gradient	-0.77
Drainage Area and Bankfull Discharge	-0.78

Median grain size (D_{50}) decreases downstream (Table 4.12) in accordance with channel theory (Bluck, 1974; Knighton, 1987). Although this is the case, at certain sites (3, 7, 17), high D_{50}'s are also encountered. These sites also tend to have higher widths and steeper gradients (Figure 4.2). Although there is progressive downstream fining, certain sites show inconsistency with progressive downstream change. At these sites local control variables may be more important in determining channel form than downstream changes in discharge.

Gradient decreases with increasing drainage area, concurring with traditional theory (Bluck, 1974; Knighton, 1987) (Table 4.12). Again, although this is the general trend, certain sites (7, 14, 17) appear to be inconsistent with the overall trend, indicating that local factors are important. This is further evidenced by the longitudinal decrease in estimated bankfull discharge.

Although theory would suggest that the volume of water moving longitudinally through the channel should increase between 30 to 40 percent, results from the survey indicate that estimated bankfull discharge is decreasing downstream ($r = -0.78$) (Table 4.12). The importance of this observation is that traditionally discharge is the major independent variable affecting channel form. This does not hold true for the 17 km surveyed length of the Bell river. Therefore factors other than discharge may be more important in controlling channel form. In effect this alters discharge from being an independent to a dependent variable, in the sense that the Q_b value as estimated in the field is dependent on channel form, and not channel form dependent on Q_b.

From the evidence provided, it would appear that due to few systematic progressive downstream changes, local conditions are more important in determining channel form than longitudinal discharge variations. This is, however, partly a function of scale, since there is no significant increase in estimated discharge there is no significant channel response.

4.5.4 CHANNEL PATTERN THRESHOLDS

Having determined estimated bankfull discharge at each selected site (see Equation 4.4), the results were plotted on Leopold and Wolman's (1957) discharge-slope threshold curve. This enabled the determination of potential channel pattern based on threshold limits.

Potential thresholds slopes for braiding were determined through a number of empirical equations identified from the literature. A number of threshold slopes for braiding (Sb) were calculated:

Leopold and Wolman, (1957) (Gravel Beds)

$$Sb = 0.013\ Q^{-0.44}\ ...\ (Eq.\ 4.10)$$

Where: Q is bankfull discharge

Ackers, (1982) (Sand Beds)

$$Sb = 0.008\ Q^{-0.21}\ ...\ (Eq.\ 4.11)$$

Where: Q is bankfull discharge

The relationship between channel pattern and the threshold slope for braiding (Sb) has further been related to bed material (D_{50}) where:

$$Sb = 0.0002\ D_{50}^{1.14}\ Q_b^{-0.44}\ ...\ (Eq.\ 4.12)$$

Where: D_{50} is median grain size
Q_b is bankfull discharge

The relationship between bank material and Sb (Ferguson, 1981) has been identified as:

$$Sb = 0.0028\ Q_b^{-0.34}\ B^{0.9}\ ...\ (Eq.\ 4.13)$$

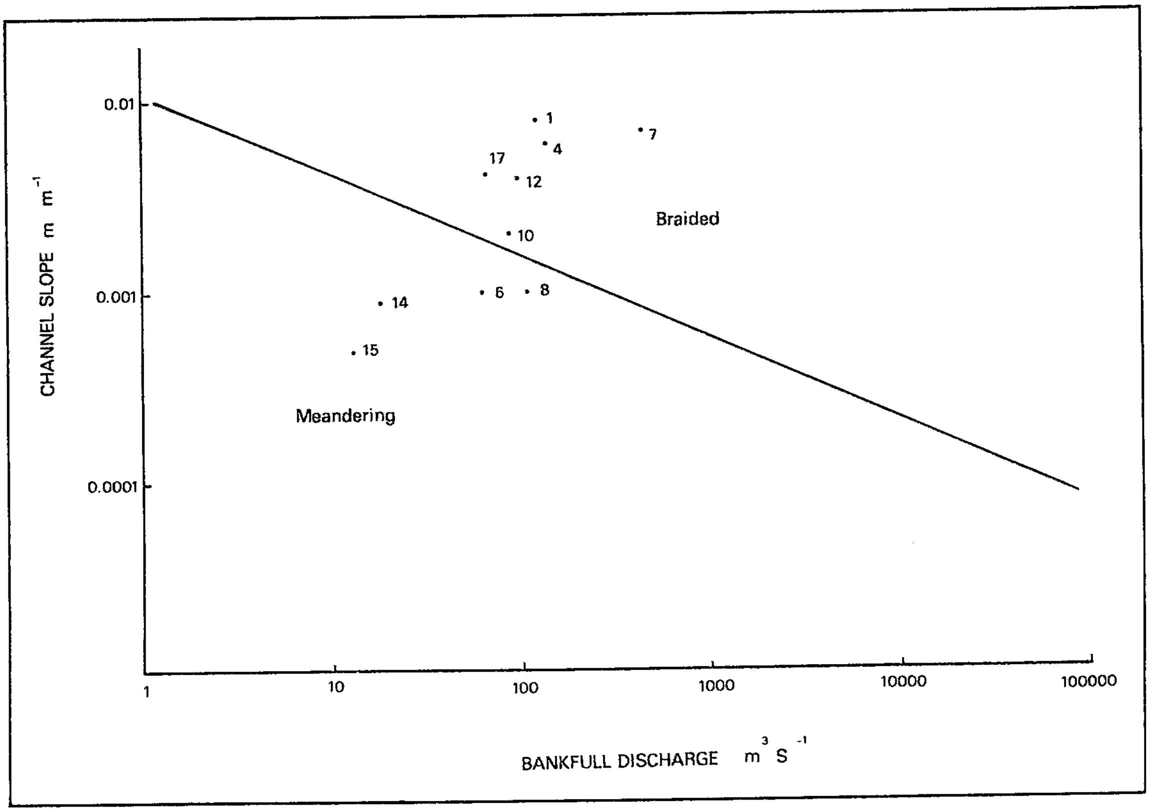
Where: B is the silt-clay percentage in the bank

Using the above empirical equations it was possible to determine (under natural conditions) the threshold slope for braiding for the Bell river (given the limitations of using empirical equations derived from other data).

4.5.4.1 Thresholds for Meandering and Braiding

The determination of potential channel pattern for selected sites for the Bell river using Leopold and Wolman's (1957) threshold curve, are presented in Figure 4.3. Of the ten reaches surveyed, 6 plot as potentially braided (1, 4, 7, 10, 12, 17) and four as potentially meandering (6, 8, 14, 15). Site 4 and 12 have been identified as meandering sections (see Table 4.3), yet plot as braided channels. These results may be misinterpreted. Site 14 and 15 are downstream of site 7 and should therefore accommodate an equal if not greater discharge. However, the estimated bankfull discharge at site 7 is over 10 times the order of magnitude of site 14 and 15 (Table 4.5). This would indicate that bankfull discharge has a very different relationship to channel form and pattern at different sites. It also shows that bankfull discharge (as estimated through field estimates) no longer serves as an effective independent channel forming variable that can be used to predict channel form and pattern. Slope-discharge predictive thresholds do not apply to the 17 km surveyed reach of the Bell river.

Figure 4.3: Potential Channel Pattern, Bell River (After Leopold and Wolman, 1957)



A summary of the results of threshold relationships for braided channels is given in Figure 4.4.

Figure 4.4: Channel Pattern Relationships: Threshold Slopes for Braiding (Sb).

RELATIONSHIP TO BANKFULL DISCHARGE (Q_b (m^3sec^{-1}))

(Equation 4.10) Gravel-Bed Streams Where Q_b = 90 Sb = 0.0018

(Equation 4.11) Sand-Bed Streams Where Q_b = 90 Sb = 0.0008

MOST REACHES (SAND AND GRAVEL BEDS) ABOVE THRESHOLD FOR BRAIDING

RELATIONSHIP TO BED MATERIAL (D_{50} (mm))

(Equation 4.12) Where D_{50} = 1 Sb = 0.00003
D_{50} = 10 Sb = 0.00038
D_{50} = 20 Sb = 0.00084
D_{50} = 60 Sb = 0.00294

MOST REACHES ABOVE THRESHOLD FOR BRAIDING

RELATIONSHIP TO CHANNEL PERIMETER MATERIAL (B (%))

(Equation 4.13) Where B = 13 Sb = 0.0060
B = 25 Sb = 0.0110
B = 70 Sb = 0.0280

CHANNEL REACHES WITH LOW SILT-CLAY CLOSE TO BRAIDING THRESHOLD

CHANNEL REACHES WITH HIGHER SILT-CLAY BELOW BRAIDING THRESHOLD

MOST REACHES ABOVE THRESHOLD FOR BRAIDING

The results indicate that if bed material alone is taken into account then most surveyed reaches in the Bell river are above the threshold slope for braiding. The results also indicate that all the sand-bed reaches are above the threshold slope for braiding. Gravel-bed streams require significantly higher threshold slopes for braiding. However, when bank resistance is taken into account, reaches with low silt-clay contents are close to the braiding threshold, whereas those reaches with higher silt-clay contents are below the threshold for braiding. Steeper threshold slopes are required for braiding in channels that have resistant banks. Clearly, the Bell river channel is either close to, or above the threshold slope for braiding and is therefore likely to show signs of channel instability. It has been stated that braided channels are often associated with channel instability and aggradation (Harvey, 1991).

4.6 DISCUSSION OF RESULTS AND CONCLUSION

From the evidence presented in this chapter, it would appear that channel bed material and riparian vegetation are the two main determinants of channel form and pattern, and that spatial variations in discharge, as estimated in the field, cannot be related to channel form. Wide, shallower, more unstable channel reaches are associated with higher calibre bed material and relatively low riparian vegetation. Narrow, stable channels are associated with finer bed material and stable tree lined banks. Channel vegetation surveys have shown that where *S. caprea* has colonized the bank, dense root matting has led to bank stabilization (see Plate 4.1). Bank vegetation has stabilized the channel banks, and induced bank accretion, resulting in the formation of channel benches (see Appendix B). Although vegetation increases bank stability through root matting and accretion, it also reduces channel capacity, increasing the potential for overbank flows and flooding (Rowntree, 1991b).

Plate 4.1: Typical *Salix caprea* Root Matting in Channel Perimeter, Bell River

Reduction in channel capacity may increase the frequency of flows greater than bankfull, thus increasing the potential for meander cutoff development. Channel form is not in adjustment to dominant discharge with a constant recurrence interval, as the literature suggests it should be (Knighton, 1987). The concept of bankfull discharge is not relevant in the 17 km surveyed reach of the Bell river since bankfull discharge cannot be considered the dominant discharge given that it is so variable downstream.

Channel straightening and instability has been attributed to increased sediment loading by many authors (Knox, 1977; Erskine, 1986; Warner, 1987). Any increase in the volume or calibre of the bed material in the Bell river may result in channel widening and possibly straightening. Increased bed material calibre would increase the threshold slope for braiding, while the introduction of finer material may reduce the threshold for braiding and therefore promote instability. The possibility of increased sediment loading in the stream will be discussed in Chapter 6.

Two distinct groups of stream beds have been identified. A gravel-bed stream (sites 1-7) and a sand-bed stream (sites 8-17), each with distinct form ratios and channel gradients. As has been previously mentioned, the incidence of major instability in the Bell river has been in the transitional zone between the upper, coarser reaches and the lower, finer reaches. Warner (1987) has pointed out (see Chapter 2) that the areas most likely to be unstable are where bed and banks are most easily mobilized. The most important factor in determining the stability of the channel is therefore its location in the long profile. This transition zone is seldom in equilibrium (Pickup, 1986) and thus has great potential for instability.

Channel straightening with attendant steepening has changed the channel pattern of certain stretches in the Bell river (see Table 4.4). Channel pattern has changed from a meandering to a braided pattern (Brice's, 1964 classification). Based on contemporary theory, it is suggested that the cause of channel steepening, braiding and instability in the Bell river may be due to a change in an external variable such as increased sediment loading or a changing climatic regime.

Channel straightening, instability and sinuosity reductions have been noted in the Bell river. It is clear from the evidence presented in the Chapter, that the Bell river is not a stable equilibrium channel and can be considered to be unstable. In the surveyed 17 km reach, many inconsistencies existed including: longitudinal reduction in channel form dimensions, longitudinal reduction in estimated bankfull discharge, inconsistency between predicted and calculated channel pattern. Clearly, local factors such as sediment characteristics and vegetation are more important than discharge in determining channel form. Sediment characteristics in the channel are primarily a function of in-channel storage and catchment condition. Channel form change in the Bell river may be related to changes in external variables such as discharge and sediment yield (temporal controls).

The following two chapters will attempt to determine whether there has been a change in the temporal controls on the Bell river. It has been noted that spatial controls determine the type and nature of channel response to changes in temporal factors, such as discharge and hydraulic regime, which initiate and determine the nature and rate of adjustment.

CHAPTER 5

RAINFALL TRENDS IN THE BELL RIVER CATCHMENT

5.1 INTRODUCTION

The evidence presented in Chapter 2 has demonstrated that a changing climate may be responsible for causing channel change and instability in a river system. This was found to be the case in the MacDonald river in Australia by Warner (1987). Harvey (1991) indicated that climatic changes are important both in terms of catchment processes (runoff and erosion on hillslopes) and channel processes (magnitude and frequency of flow events and sediment regime).

Based on research by other authors (Warner, 1987, Eybergen and Imeson, 1989), it was hypothesized that a changing climatic regime in the Bell river catchment may be responsible for affecting changes in catchment and channel processes, causing channel change. To test this hypothesis, it was necessary to examine rainfall and flow data in the catchment to test for possible rainfall and flow variations. Rainfall data was available for the catchment. No gauging weir, however, was available to determine flow variations in the Bell river. Flow data from the Kraai river, downstream of the Bell was used in order to document regional floods and flow variations.

5.2 AIMS AND OBJECTIVES

In order to determine the above mentioned, the following aim and objectives were identified:

5.2.1 Aim

To determine whether there has been any medium term (less than 100 years) progressive trend in the rainfall pattern of the Bell river catchment in terms of annual, seasonal and daily rainfall.

5.2.2 Objectives

In order to achieve this aim, the following objectives were identified:

a) To determine medium term climatic trends for annual and seasonal rainfall data using statistical techniques, these include:

1) Regression analysis
2) Standardized anomaly indices

3) Five year running means

b) Calculation of frequency tables and histograms for daily rainfall data to determine the existence of a change in the frequency distribution of daily rainfall data for the Bell river catchment.

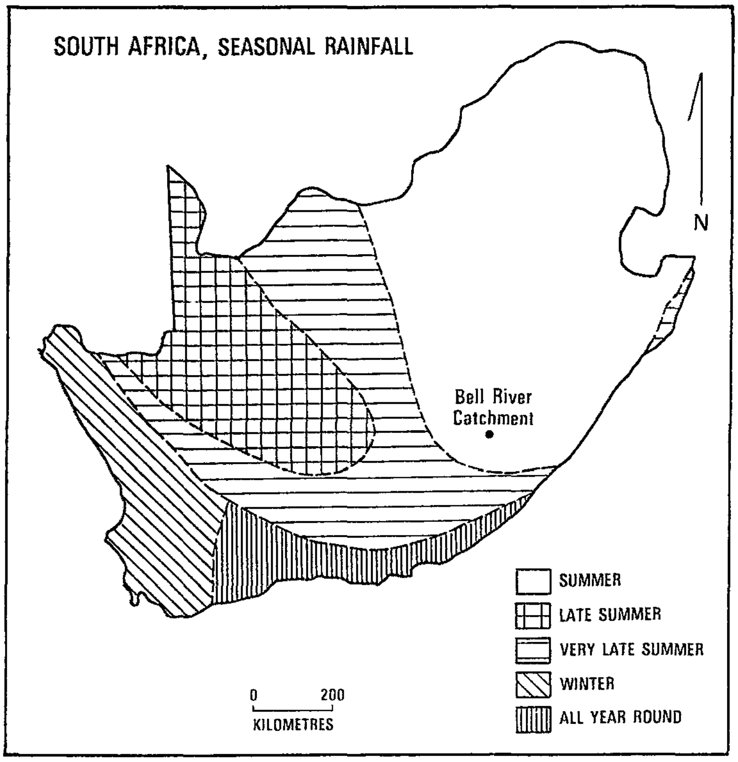
c) The documentation of regional floods through flow record data.

5.3 CLIMATE OF THE BELL RIVER CATCHMENT

The Bell River catchment lies in the north east Cape Drakensberg. The catchment is affected, as is most of southern Africa, by circulation systems in the tropics to the north and the temperate latitudes to the south (Preston-Whyte and Tyson, 1988). Consequently, South Africa is dominated by anticyclonic circulation patterns and subsidence (Tyson, 1978). Rainfall decreases from east to west in South Africa (Department of Water Affairs (DWA), 1986). The monthly distribution of the rainfall varies regionally. In the north east of the country, the rainfall season occurs in the summer (Figure 5.1), to the south west it is in winter (Tyson, 1978; DWA, 1986).

The Bell river catchment forms part of the summer rainfall region of South Africa (see Figure 5.1). Due to it's altitude, the catchment also receives snow in the form of intermittent fall and melt. Unfortunately no instruments are available to measure the volume or areal extent of the snow.

Figure 5.1: Relationship of the Bell River Catchment to the Summer Rainfall Region of South Africa



5.4 CLIMATIC FLUCTUATIONS AND PROGRESSIVE TRENDS

At this point it is important to distinguish between what is termed a progressive climatic trend and a climatic fluctuation. A progressive trend refers to a state where there is a gradual increase or decrease in volume of rainfall for a given area over a specified time (Figure 5.2a). A climatic fluctuation refers to a fluctuation around a steady state mean (Figure 5.2b).

Progressive climatic trends not only affect the amount and type of rainfall, but also the type and condition of the vegetation and hence the response of the hydrograph, and the erosion status of the catchment. The importance of the relationship between rainfall, runoff and vegetation is well known (Langbein and Schumm, 1958). These catchment changes in turn have a direct impact on the nature of the hydraulic and sediment regime of the river channel (Dent *et al*, 1987). Eybergen and Imeson (1989) state that precipitation changes have important geomorphic effects where small variations in some instances may have a significant effect on vegetation and hence erosion.

Figure 5.2a: A Progressive Climatic Trend

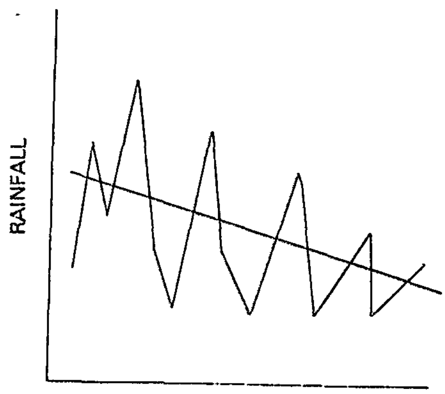
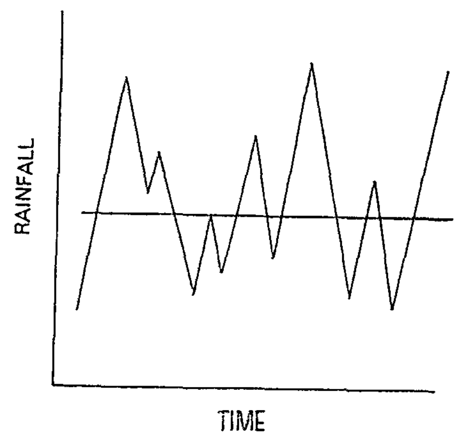


Figure 5.2b: A Climatic Fluctuation



Studies of climatological data throughout the world during the past century have indicated that climate is seldom, if ever, constant (World Meteorological Organisation (WMO), 1966). Climatic fluctuations, can be determined according to the WMO (1966) in seven distinct phases:

1) The reliable measurement of the data.
2) The statistical interpretation of the fluctuations.
3) The description of fluctuation in detail.
4) The immediate cause of the fluctuations.
5) The ultimate causes of the fluctuations.
6) The prediction of future fluctuations.
7) The effects of climatic fluctuations on environmental resources and human activities.

5.5 STATISTICAL EVIDENCE FOR CLIMATIC FLUCTUATIONS FOR THE PERIOD OF METEOROLOGICAL RECORD

Tyson (1986) demonstrates the cyclical nature of the pattern of South African rainfall, especially for the summer regions in the north east of South Africa. Rainfall in the summer rainfall region is experienced in distinctive wet and dry cycles within each year as well as alternating years of drought. Variance peaks in the region of 18-22 years are common, although most peaks occur at around 18 years. These peaks are experienced elsewhere in southern Africa. Mazvimawi (1989) using annual rainfall for 20 stations in Zimbabwe for the period 1891-1988 found similar variance peaks. Vines (1980) found that periodic fluctuations similar to those present in annual rainfall in South African rainfall, were found in SE Australia and New Zealand.

The 18 year peak has been identified by Dyer and Tyson (1977) and Dyer (1975), using principle component analysis of a regionally synthesized rainfall series followed by a spectral analysis of the rainfall series. It should be stated that these variations were calculated for a regional data series, and although no long term progressive trend in the series had occurred, it is possible to have individual stations showing a progressive climatic trend.

The 18 year quasi biennial fluctuation implies that there will be periods of high and low rainfall in southern African historical series. Dyer and Tyson (1977) predicted that the periods 1972-1981 and 1981-1990 were likely to produce below normal rainfall. Similar predictions have been made by Lindesay (1984) and Dent *et al* (1985). Tyson (1978) indicated that space mean percentage deviations clearly show how decades 1916 to 1925, 1936 to 1944, and 1954 to 1963 experienced above average rainfall, whereas the decades in between experienced below average conditions. Temperatures were 180^0 out of phase with the rainfall oscillations.

Although the 18 year cycle is fairly well established in the southern African literature, no evidence has been found to suggest that there have been any long term trends for the period of meteorological record (Tyson and

Dyer, 1975). Vogel (1988) states that temporal characteristics of rainfall in southern Africa have remained essentially the same for the past two centuries. This is further confirmed by Tyson (1986) and Dent *et al* (1987). Dyer (1982) examined the hypothesis that there had been an upward trend in the annual rainfall over southern Africa during the period 1921-1974 and rejected that possibility on the basis of the lack of statistical evidence.

Louw (1965) states that the popular belief that rainfall had been decreasing can be attributed to human perception. In his analysis of 12 rainfall stations each containing more than 60 years of record, no evidence could be found to suggest a progressive trend in any of the time series. Linear regression analysis of a rainfall series by Brook and Mametse (1970) found that while some parts of South Africa were experiencing a progressive positive trend, others were experiencing a progressive negative trend. As the Bell river catchment forms part of the summer rainfall region of South Africa, it may be possible for the catchment to experience a progressive trend in rainfall.

5.6 STATISTICAL PARAMETERS FOR DETERMINING CLIMATIC FLUCTUATIONS

The statistical analysis of a long series of climatological information generally leads to a loss in the total amount of information (Godske, 1959).

The WMO (1974) states that the choice of a station for statistical analysis should be based on a period long enough to represent a good sample record through time. Too short a period may be influenced by a particular wet or dry cycle, too long a period will require a lengthy synthesis of data. Non-parametric tests conducted by Tyson (1986), showed that the occurrence of trend is highly dependent on the length of data and period of record. WMO (1966) states that too short a period of meteorological record could seriously bias the estimate of mean annual precipitation, this bias is more pronounced in a semi-arid area (Dent *et al*, 1987). The length of record required in semi-arid regions is often longer than that required in a humid region, due to the high degree of spatial and temporal variance (Nicholson, 1986; Rowntree, 1988a, 1989; Hulme, 1990). The study of climatic fluctuations is then essentially a problem of time series analysis.

Numerous methods of analysis have been used or suggested in the past to describe climatic change. The use of a weighted moving average (Craddock, 1957), frequency distributions (Conrad and Pollack, 1950; Craddock, 1965), the calculation of percentage deviations from the mean (Dent *et al*, 1987) the common use of residual mass curves (Kraus, 1955), least squares method (Vorster, 1957; Brooke and Mametse, 1970; Dent *et al*, 1987), principle component analysis (Dyer, 1975 and 1982, Tyson, 1986), the percentage deviation of above and below normal rainfall as estimated using a polar planimeter (Lindesay, 1984), a relative conditional probability distribution (Ogawara, 1955) and coefficient of variation (Longely, 1952; Dent *et al*, 1987) have been applied.

No single method for determining climatic fluctuation appears to be dominant in the literature. The methodology applied seems to depend on the type of rainfall series used, the length of data series, and most importantly, the type of information and statistical parameters required from the data series.

5.7 METHODOLOGY: ANNUAL RAINFALL DATA

Four stations in and around the Bell river catchment (see Figure 1.1) were chosen for statistical analysis (Table 5.1). These stations were chosen on the basis of length of record, proximity to the catchment and reliability of data. The four stations that were chosen for analysis, Rhodes Police (1973-1990), Malpas (1923-1983), Funnystone (1923-1986) and Barkly East (1901-1990), consisted of data augmented by the Computing Centre for Water Research (CCWR). Although Barkly East lies some 50 km east of the catchment, and receives considerably less rainfall, it was included as it was the only station whose data extended to the beginning of the century. Barkly East was used primarily to extend the rainfall record in order to determine rainfall trends at the beginning of the 1900s.

The stations were analyzed using a simple linear regression (Johnston, 1978), and Pearsons product moment correlation coefficient for use on parametric data at the interval level (Ebdon, 1985). Dent *et al* (1987) states that linear regression analysis is a common form of rainfall analysis, and can be used as a predictive tool.

It should be noted that when using a regression equation, the closer the correlation coefficient between the two variables, the greater the predictive capability of the regression (Hammond and McCullagh, 1978). Dyer (1982) suggests the following criteria with respect to the use of linear regression to extend a data series for South African rainfall series: the series have at least a 15 year concurrent record, and have a correlation coefficient of more than 0.5 with a target site.

A regional data series was generated based on the high correlation coefficients obtained for the annual data between the stations (Table 5.2). This consisted of the averages of three rainfall stations (Rhodes Police, Malpas and Funnystone). Where data did not overlap, a regression was used to extend each data series to the same time span. Barkly East was not used, as the average rainfall received is considerably less than the other three stations, and therefore would reduce rainfall averages of the regional data, resulting in inaccurate data.

To determine whether there has been a progressive trend in the rainfall data, a regression was performed on each of the rainfall series through time (including the regionalized data set). The trend was thus expressed as the regression of precipitation (dependent variable) through time in years (independent variable).

Standardized Anomaly Indices (SAI's) were calculated for each of the annual series (Eq. 5.1). The SAI is a commonly used index for determining climatic fluctuation (Katz and Glantz, 1986; Hulme, 1990). The index provides an index of relative rainfall yields based on the standardization of rainfall (z-score). The construction of the index involves subtracting the historical mean from each yearly total and dividing by the historical standard deviation. The rainfall indices are averaged for all years for one station to produce a z-score.

$$\text{SAI (z-score)} = \frac{\text{Yearly Total - Historical Mean}}{\text{Historical Standard Deviation}} \quad \text{... (Eq. 5.1)}$$

Moving averages are used as a method of smoothing a data series, allowing the easy recognition of wet and dry periods. A five year moving average was used in this analysis. Using these statistical techniques, it was possible to determine whether progressive changes had occurred in the volume and trend of the annual rainfall, as well as displaying cycles and fluctuations in the rainfall.

5.8 RESULTS

5.8.1 Annual Series

Table 5.1 depicts the summary statistics for each rainfall station for the annual series.

Table 5.1: Summary Statistics, Rainfall Series

VARIABLE	FUNNYSTONE	MALPAS	RHODES POLICE	BARKLY EAST
Date	1923-1986	1923-1983	1973-1990	1901-1990
Altitude (m)	1850	1800	1820	1780
Sample size	64	61	18	90
Mean	810.698	694.03	708.36	618.49
Median	806.9	688.7	700.4	606
Mode	793.4	685.3	691.8	633
Standard Deviation	157.5	140.561	117.132	126.87
Maximum	1149.7	1004.4	920.5	942
Minimum	535.3	412	533.9	327

The least squares regression expressed as a linear model **y = a + b X**, was used to express trends and relationships between data series. Table 5.2 depicts the results obtained from the analysis. Figure 5.3 shows the plot and the regression line between the different data series. All stations show significant positive interrelationships.

Table 5.2: Regression Analysis, Bell River Rainfall Stations (* significant at 0.05 level)

VARIABLES	REGRESSION EQUATION	CORRELATION COEFFICIENT
Rhodes Police on Funnystone	Y = 232.25 + 0.55 X	0.83 *
Rhodes Police on Malpas	Y = 316.68 + 0.55 X	0.78 *
Funnystone on Malpas	Y = 136.29 + 0.98 X	0.86 *
Rhodes Police on Barkly East	Y = 330.40 + 0.59 X	0.70 *
Malpas on Barkly East	Y = 207.10 + 0.76 X	0.73 *
Funnystone on Barkly East	Y = 222.58 + 0.92 X	0.78 *

The regionalized data set produced based on the high r values is given in Figure 5.4.

The expression **Y = a + b X** was performed for the five series on time. The results of this analysis is depicted in Table 5.3. The plot of the regression of each data series on time is produced in Figure 5.4. No significant relationship exists between any of the rainfall series and time.

Table 5.3: Regression Analysis, Bell River Rainfall Stations on Time (* significant at 0.05 level)

VARIABLES	REGRESSION EQUATION	CORRELATION COEFFICIENT
Rhodes Police on Time	Y = 8625.37 + (-3.99) X	-0.18
Malpas on Time	Y = 3145.69 + (-1.25) X	-0.15
Funnystone on Time	Y = 686.02 + 0.06 X	0.0007
Barkly East on Time	Y = -1183.56 + 0.92 X	0.19
Regional Data on Time	Y = 836.51 + (-0.05) X	-0.008

SAI's are plotted for the five series (Figure 5.5). Clear, alternating cycles of wet and dry rainfall periods exist. The five year running mean shows a similar relationship with the smoothed curves showing wet and dry cycles more clearly (Figure 5.6).

Figure 5.3: Between Station Regressions, Rainfall Stations

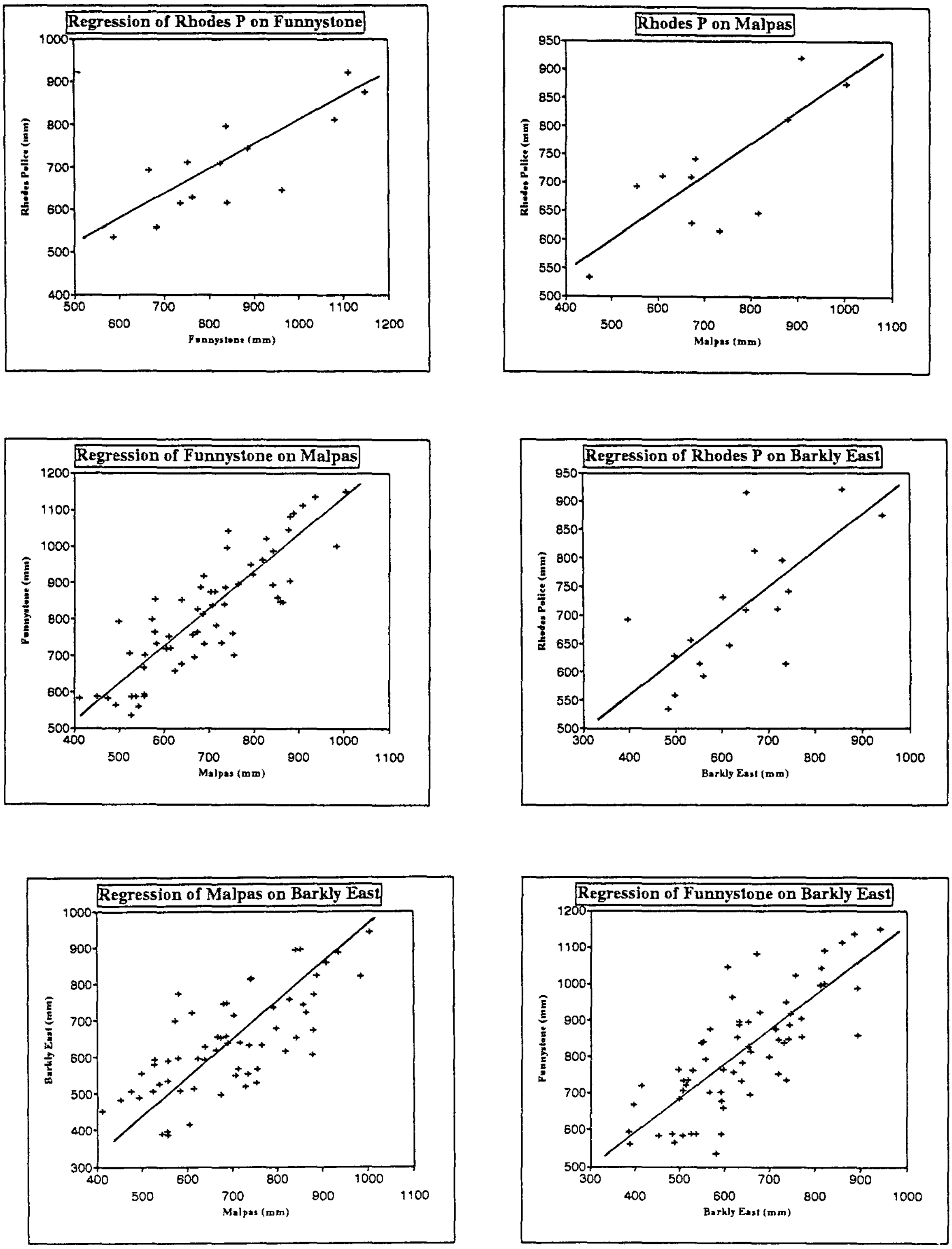


Figure 5.4: Regression of Rainfall on Time (Annual Series)

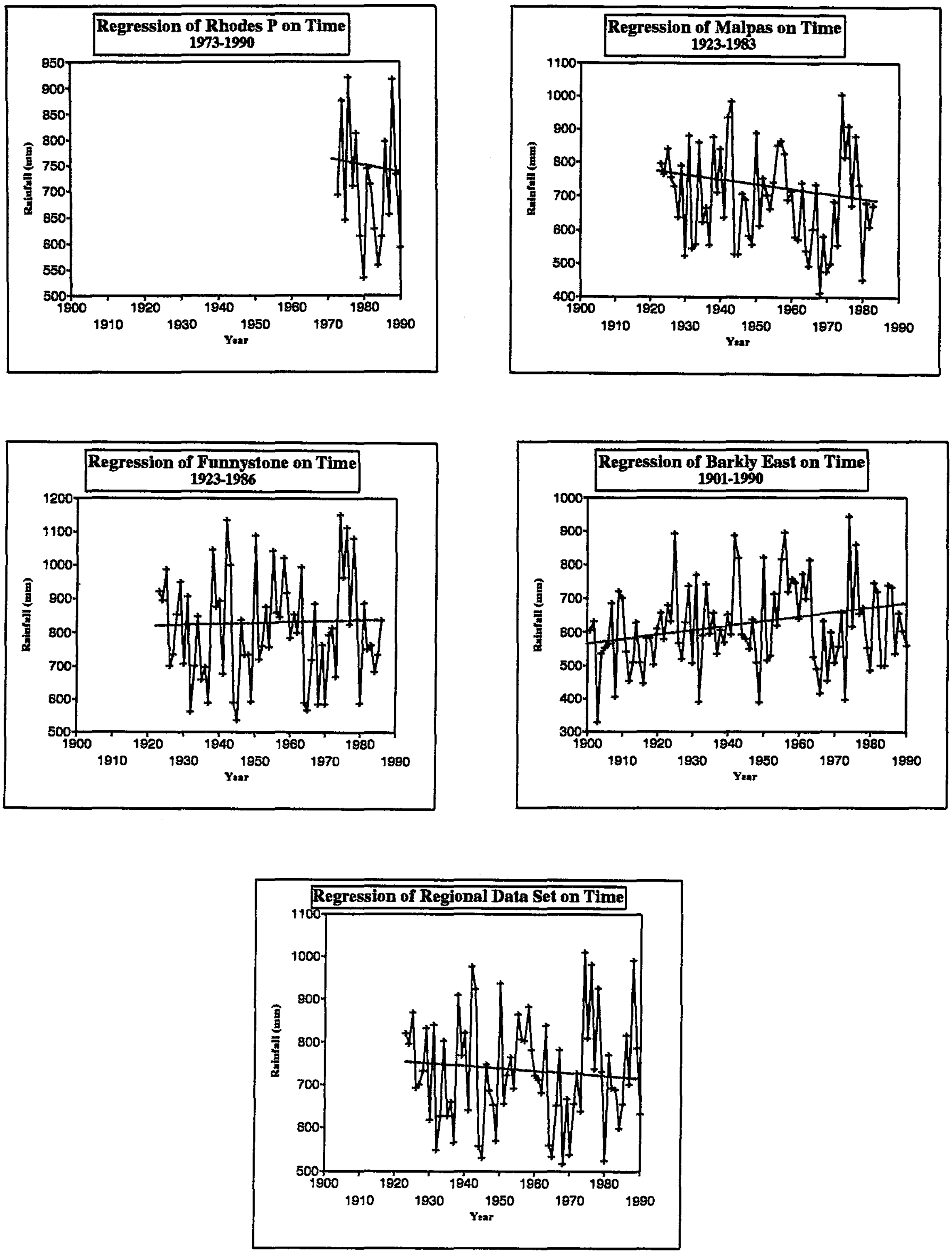
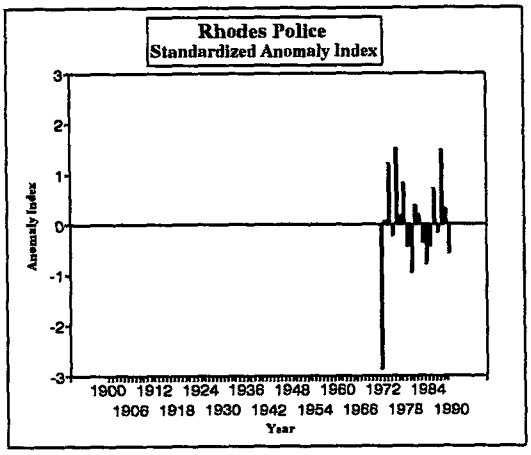
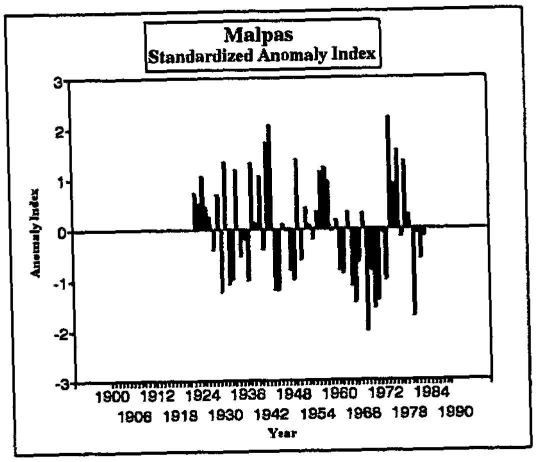
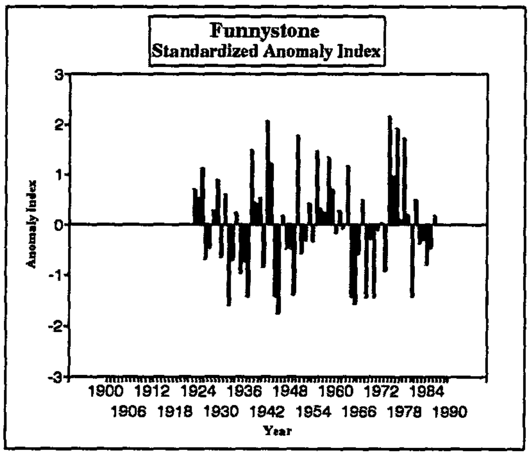
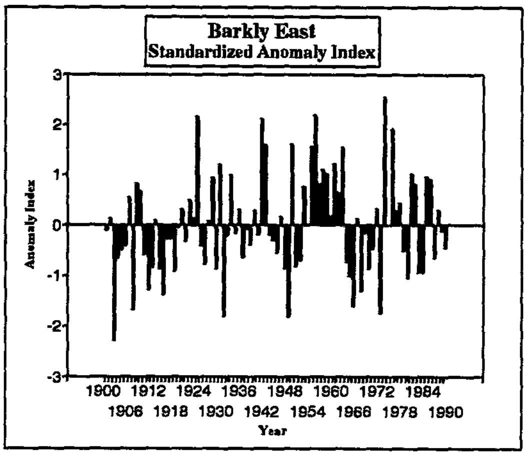


Figure 5.5: Standardized Anomaly Indices, Rainfall Stations









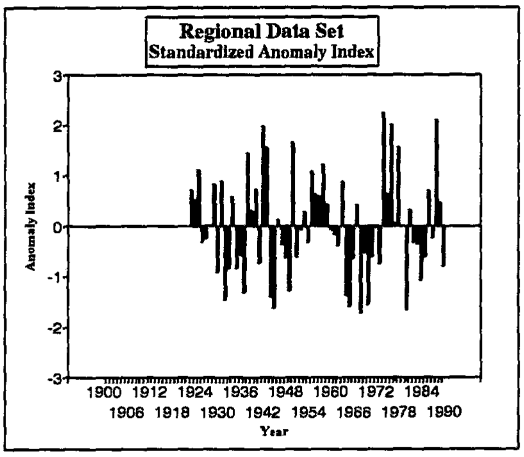
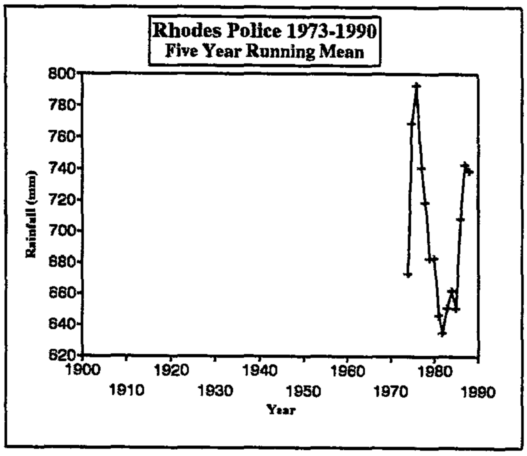
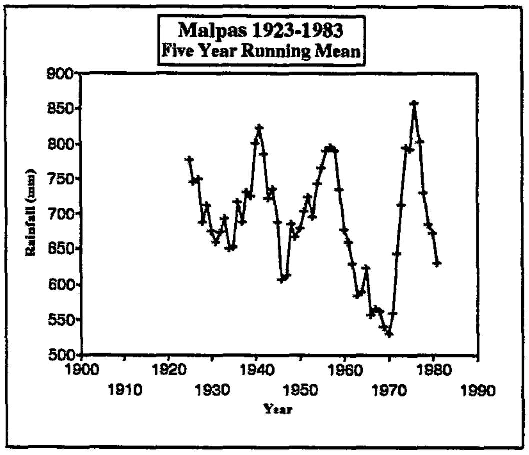
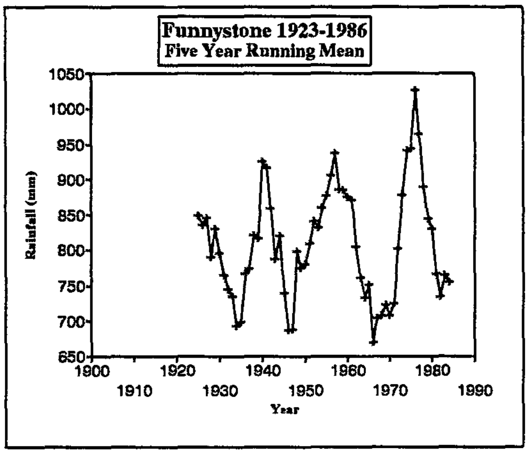
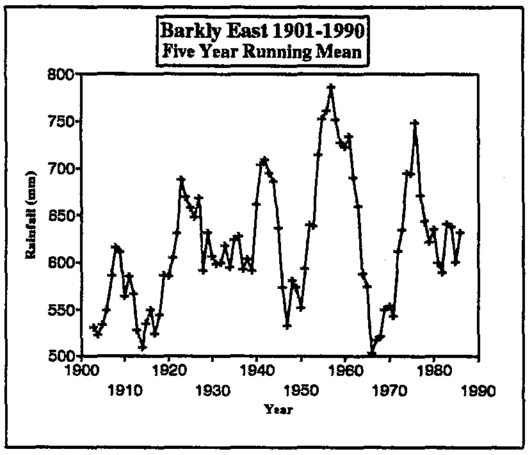


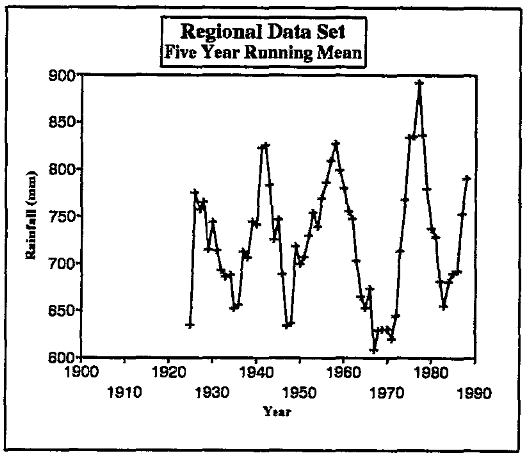
Figure 5.6: Five Year Running Means, Rainfall Stations











5.8.2 Discussion of Results

Results of the regressions of the rainfall stations on time (Table 5.3) indicate the absence of any progressive trend in the annual series. Even though weak positive and negative slopes are evident in the expression, these are all statistically insignificant. This finding conforms with results obtained by other authors (Tyson (1986) for example) in South Africa, who found no evidence to suggest a progressive trend in rainfall in the summer rainfall region.

Even though no long term progressive trend exists, it is clear that there is a cyclical pattern in the rainfall pattern. The SAI's and 5 year running means show this clearly, with peaks occurring in all series at around 15-19 years. This concurs with the work done by Dyer (1975) and Dyer and Tyson (1977) who found variance peaks in South African summer rainfall around 18-22 years.

Clearly then, for the annual series, climatic fluctuations, rather than progressive climatic trends dominate the rainfall pattern of the Bell river catchment. The relationship between wet and dry periods, the length of the periods and maximum and minimum rainfall are the important themes in the rainfall pattern. Similar relationships have been found in Australia and have been termed Drought Dominated Regimes (DDR) and Flood Dominated Regimes (FDR) (Warner, 1987). Having eliminated progressive climatic trend as a variable effecting catchment and channel processes, one could conclude that for the Bell river catchment, the magnitude and frequency of events are more significant than progressive rainfall trends.

5.9 SEASONAL DATA

5.9.1: Methodology

Erskine (1986) suggested that although the absence of a progressive annual fluctuation in rainfall might be evident, a change in the seasonality of the rainfall may trigger channel instability. Based on this, it was hypothesised that a change in the seasonality of the rainfall of the Bell river catchment may be responsible for triggering channel instability. To test this hypothesis the following analysis was performed.

The data were divided into summer and winter rainfall series using the following procedure. The percentage rainfall produced by each month for each year was calculated. The mean rainfall percentage contribution for each month for the entire series was determined. Based on this, each year was divided into a summer rainfall series (those months producing > 8 percent of the mean annual rainfall), and a winter rainfall series (those months producing < 8 percent of the mean annual rainfall).

Simple linear regression analysis for each season for each rainfall station was performed. In this manner it was possible to determine progressive trends in seasonal precipitation.

5.9.2 Results

Table 5.4 indicates which months were combined to produce seasonal data, and the percentage of the mean monthly rainfall produced. This Table also indicates the clear seasonality of the rainfall with the summer months (October to March) producing on average more than 70% of the yearly rainfall.

Table 5.4: Months Contributing to Seasonal Data

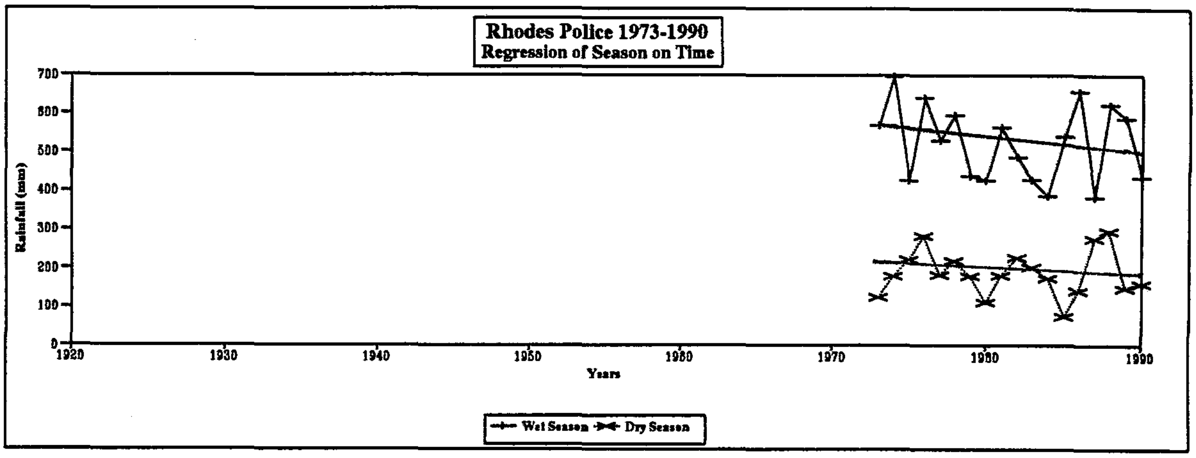
MONTH	MEAN MONTHLY PERCENT (RHODES POLICE)	MEAN MONTHLY PERCENT (MALPAS)	MEAN MONTHLY PERCENT (FUNNYSTONE)	SEASON
January	13.18	15.07	14.19	Wet
February	13.53	13.67	12.78	Wet
March	11.74	12.89	13.26	Wet
October	10.43	8.84	9.08	Wet
November	12.10	10.42	11.43	Wet
December	12.64	13.18	12.70	Wet
June	3.38	2.18	2.86	Dry
July	2.27	2.66	2.50	Dry
August	3.77	2.99	3.09	Dry
April	6.88	7.40	7.91	Dry
May	3.78	4.93	5.32	Dry
September	6.30	5.14	4.89	Dry

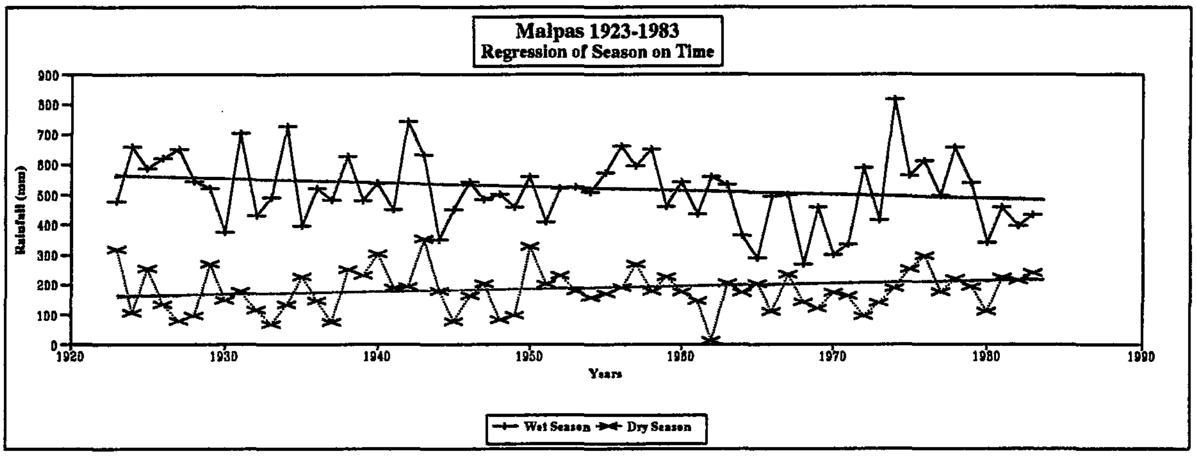
Regression analyses were performed on each season for each rainfall series. The results of these regressions are shown in Table 5.5, the plots of the results are shown in Figure 5.7. Clearly, no long term progressive trend in the seasonal data is apparent.

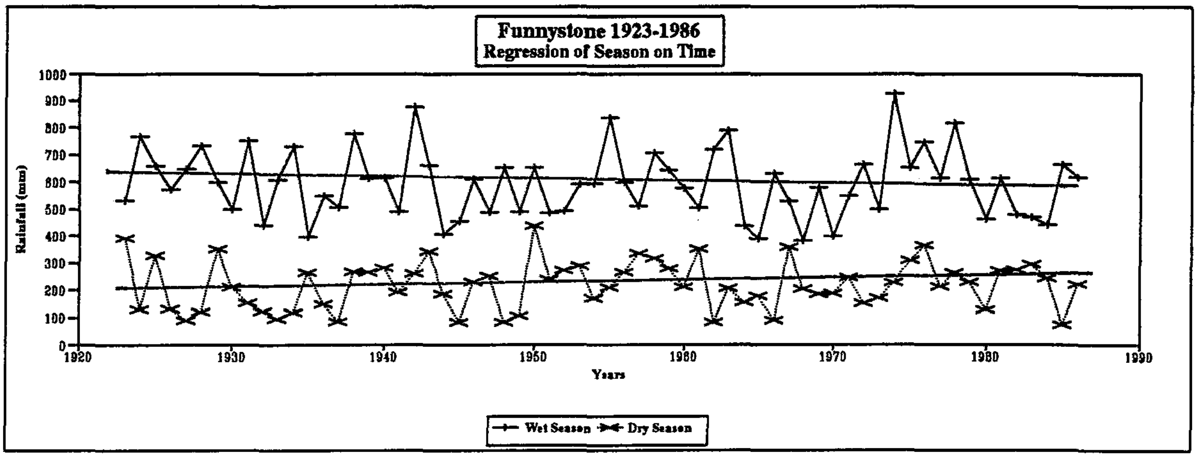
Table 5.5: Regression Analysis, Seasonal Data, Bell River Catchment (* significant at 0.05 level)

VARIABLES	REGRESSION EQUATION	CORRELATION COEFFICIENT
Rhodes Police Wet Season on Time	Y = 8216 + (-3.88) X	-0.20
Rhodes Police Dry Season on Time	Y = 408.46 + (-0.04) X	-0.01
Malpas Wet Season on Time	Y = 3497.4 + (-1.52) X	-0.23
Malpas Dry Season on Time	Y = -351.71 + 0.27 X	0.06
Funnystone Wet Season on Time	Y = 1432.03 + (-0.42) X	-0.06
Funnystone Dry Season on Time	Y = -746.00 + 0.49 X	0.10

Figure 5.7: Regression of Rainfall on Time (Seasonal Data)







5.9.3 Discussion of Results

As in the annual series, no evidence could be found to suggest a progressive trend in the seasonal data. Even though the slopes of the expressions showed weak positive and negative slopes, these were statistically insignificant at the 0.05 level.

One can conclude from these results that there is no progressive trend in the seasonal rainfall for the Bell River catchment.

5.10 DAILY DATA

5.10.1 Methodology

Daily data was obtained for three stations, Funnystone (1923-1986), Malpas (1927-1972) and Rhodes Police (1973-1990). The aim of the analysis of daily data was to determine whether there was any significant difference between the magnitude and frequency of daily events between wet and dry cycles of rainfall.

To achieve this, the data was divided into periods of wet and dry cycles based on years producing above and below average rainfall. Above and below mean rainfall for each station was determined through the use the regionalized data set in order to standardize the series for comparison. Frequency tables were calculated for the series for the wet and dry cycles. This was done for all events greater or equal to 10 mm, as it is generally accepted that 10 mm or more is required before storm runoff is produced (Rowntree, 1989).

5.10.2 Results

Frequency histograms calculated for each class for each series are presented in Tables 5.6, 5.7 and 5.8. Figures 5.8, 5.9 and 5.10 display frequency histograms calculated for Rhodes Police, Malpas and Funnystone daily rainfall.

Table 5.6: Frequency Table, Rhodes Police Daily Rainfall

LOWER LIMIT	UPPER LIMIT	FREQUENCY (WET CYCLE)		FREQUENCY (DRY CYCLE)	
Rain (mm)	Rain (mm)	n	Percentage	n	Percentage
10	<20	179	73.79	137	74.46
20	<30	42	17.36	30	16.30
30	<40	15	6.20	11	5.98
40	<50	3	1.24	3	1.63
50	<60	2	0.83	3	5.98
60	<70	0	0.00	0	1.63
70	<80	0	0.00	0	0.00
80	<90	1	0.41	0	0.00
90	<100	0	0.00	0	0.00
Total		242	100	184	100
Mean Rainfall(mm)			19.18		19.01

Figure 5.8: Frequency Histogram, Rhodes Police Daily Data

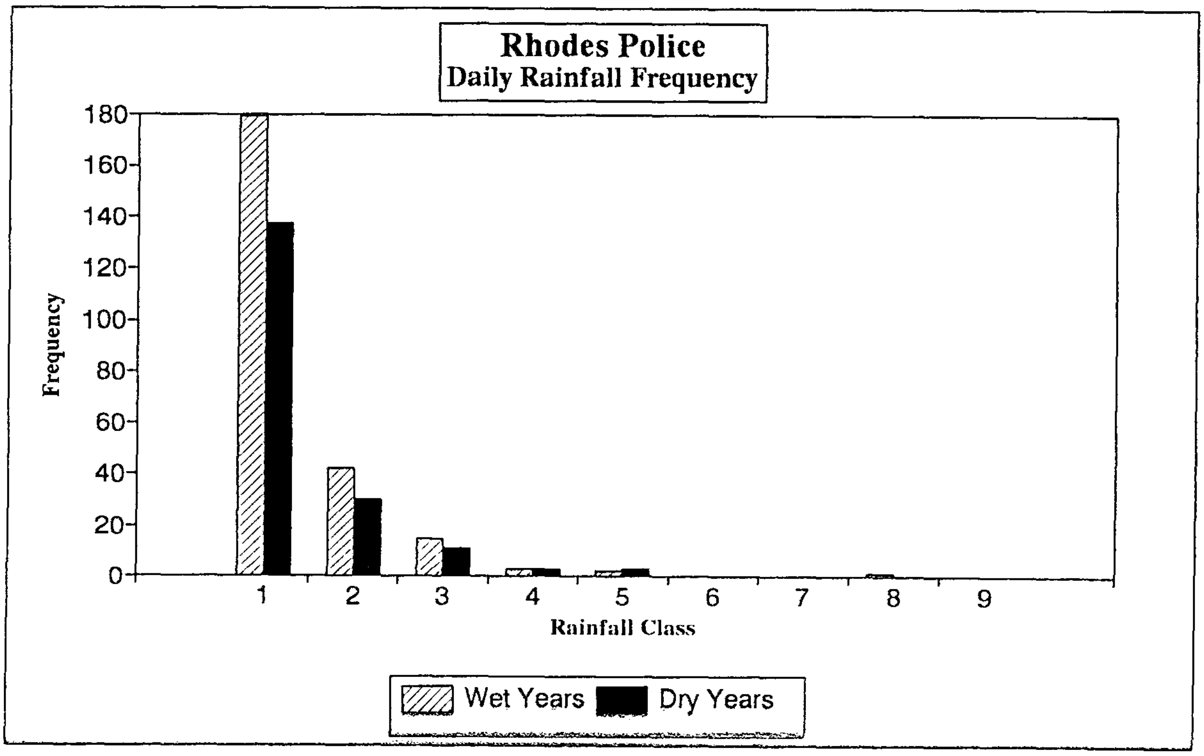


Table 5.7: Frequency Table, Malpas Daily Rainfall

LOWER LIMIT	UPPER LIMIT	FREQUENCY (WET CYCLE)		FREQUENCY (DRY CYCLE)	
Rain (mm)	Rain (mm)	n	Percentage	n	Percentage
10	<20	496	69.5	334	69.9
20	<30	164	23.0	101	21.1
30	<40	32	4.5	28	5.9
40	<50	14	3.4	11	2.3
50	<60	3	0.4	2	0.4
60	<70	3	0.4	2	0.4
70	<80	1	0.1	0	0
80	<90	1	0.1	0	0
90	<100	0	0	0	0
Total		714	100	478	100
Mean Rainfall(mm)			18.37		18.43

Figure 5.9: Frequency Histogram, Malpas Daily Data.

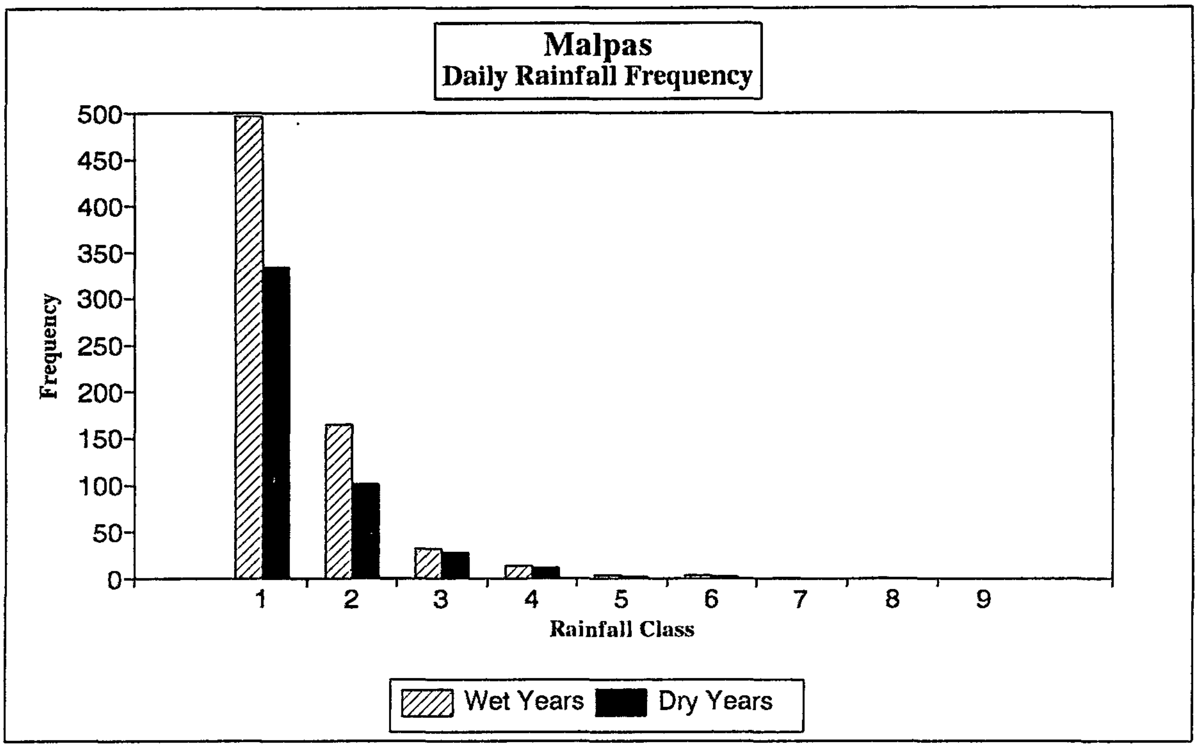
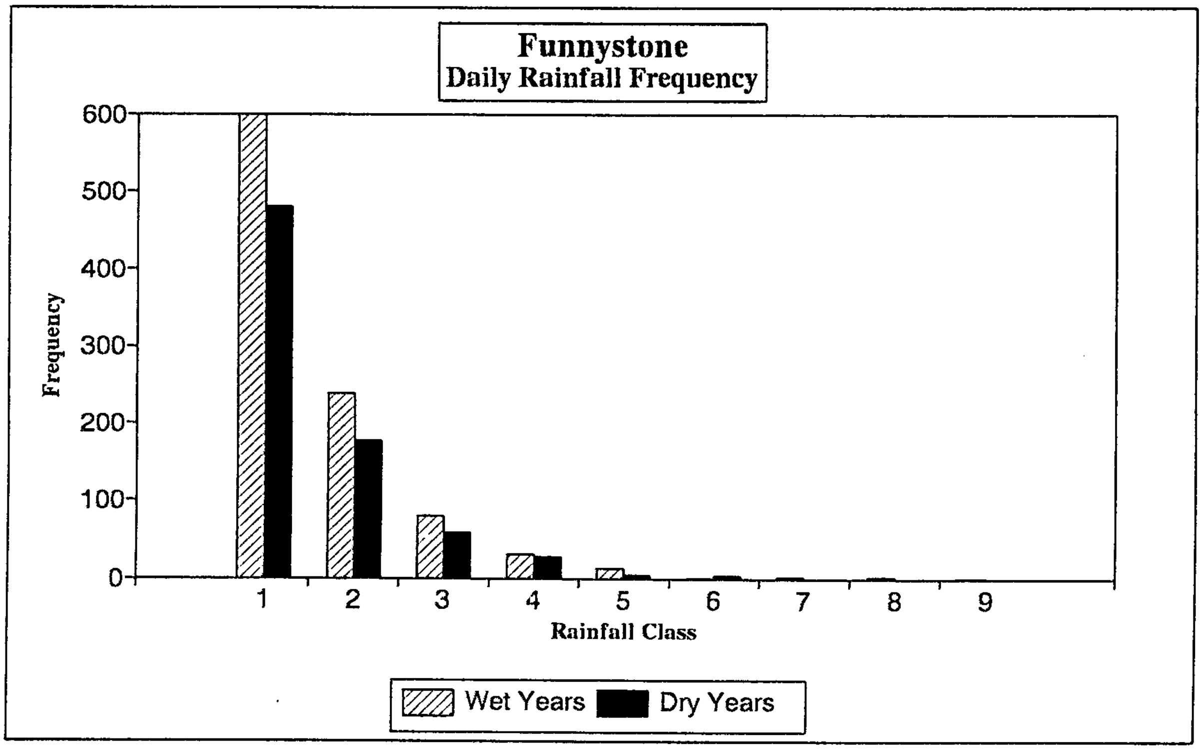


Table 5.8: Frequency Table, Funnystone Daily Rainfall

LOWER LIMIT	UPPER LIMIT	FREQUENCY (WET CYCLE)		FREQUENCY (DRY CYCLE)	
Rain (mm)	Rain (mm)	n	Percentage	n	Percentage
10	<20	599	62.00	481	64.04
20	<30	238	24.64	176	23.44
30	<40	80	8.28	59	7.86
40	<50	31	3.21	28	3.73
50	<60	12	1.24	4	0.53
60	<70	1	0.10	3	0.40
70	<80	2	0.21	0	0
80	<90	2	0.21	0	0
90	<100	1	0.1	0	0
Total		966	100	751	100
Mean Rainfall(mm)			20.35		19.79

Figure 5.10: Frequency Histogram, Funnystone Daily Data.



5.10.3 Discussion of Results

The frequency distribution of daily rainfall data for the wet and dry season for the stations shows interesting trends. For the wet periods, although the percentage frequency distribution and means are similar to those of the dry periods, the frequency of events is greater for the wet periods (Table 5.6, 5.7 and 5.8 and Figures 5.8, 5.9 and 5.10). Wet periods also show the incidence of higher rainfall events, with higher magnitude events occurring during wet periods. Even though they are insignificant in terms of overall contribution to rainfall, they may be significant in terms of flood events.

It is clear that wet and dry cycles are a response to changes in the frequency of daily events, rather than an increase in the magnitude of events. It is apparent that wet periods also produce higher intensity events, but are not significant in terms of overall contribution to the rainfall. Infrequent high intensity events may however be important in terms of geomorphic thresholds.

5.11 FLOW DATA

5.11.1 Methodology

The aim of the analysis is to examine regional flow fluctuations, and to determine whether these can be correlated to rainfall fluctuations in the Bell river catchment. To do this, regional discharge must correlate with upper catchment rainfall. If a correlation exists, then one can assume that regional flow variations reflect flow variations in the Bell river. Flow data were obtained from the Department of Water Affairs for the flow gauging weir DIH011 on the Kraai River, downstream of the Bell river. The Kraai river starts at the junction of the Bell and Bokspruit rivers, and forms part of the Orange river system. The weir D1H011 records the drainage of 8688 square kilometres, an area 20 times that of the Bell river catchment. The gauging station has a record from 1965 to 1989. It is situated some 213 kilometres west north west of the Bell River (304950 S 205517 E). Due to their mountainous nature, the Bell and Bokspruit rivers contribute a high percentage of flow to the Kraai system (Pitman *et al*, 1981). The station was chosen as it is the closest weir on the same drainage network as the Bell river. It should be stressed that the flow data in the Kraai river are used only as an indicator of the temporal variations of flow in the Bell river.

The flow data from D1H011 has data gaps for a number of years. It would therefore be erroneous to correlate annual flow with annual precipitation for the four stations. To overcome this, the mean monthly flow for each year was calculated (Eq. 5.2) and correlated with the mean monthly precipitation (Eq. 5.3) for each of the rainfall stations. Simple linear regressions were also performed on the data.

$$\textbf{Mean Monthly Flow} = \frac{\sum(M_1...M_n)}{n} \quad \text{... (Eq. 5.2)}$$

Where: M_1 is month 1

M_n is month 12

n is the number of months with a complete data record

$$\textbf{Mean Monthly Precipitation} = \frac{\sum(M_1...M_{12})}{n} \quad \text{... (Eq. 5.3)}$$

Where: M_1 is month 1

M_{12} is month 12

n is the number of months with a complete data record

A flood frequency curve was constructed for the flow data (Eq. 5.6).

$$T = \frac{n+1}{m} \quad \text{... (Eq. 5.4)}$$

Where: T is recurrence Interval

n is the number of years and,

m is the rank

This method has been used previously in South Africa (Wadeson, 1989; Dollar, 1990) and a full description can be found in Dunne and Leopold (1978). This enabled the determination of the mean annual flood for the Kraai river (R.I. = 2.33) (Dunne and Leopold, 1978). From this result, an approximate bankfull discharge estimate for the Bell river could be calculated. This enabled the estimated bankfull discharges (see Equation 4.4) for the Bell river to be put into perspective.

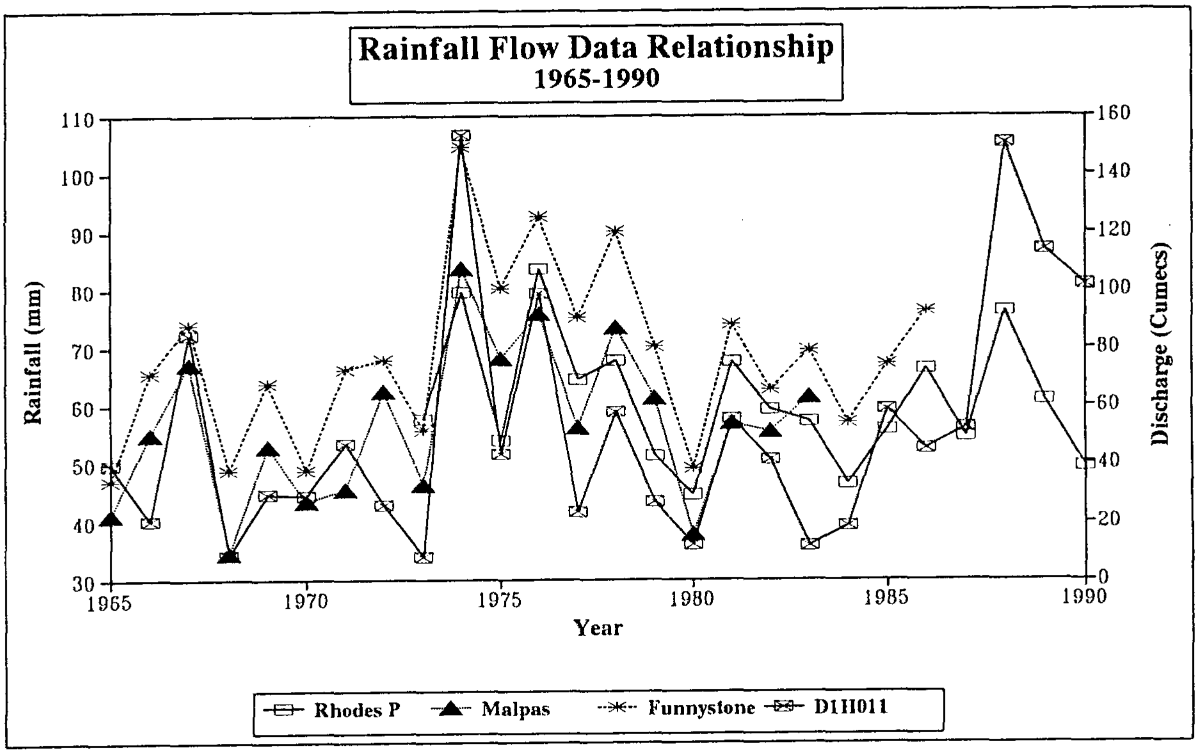
5.11.2 Results

The results of the regression of mean monthly flow data on mean monthly precipitation for the four rainfall series are depicted in Table 5.9. Figure 5.11 displays the relationship between mean monthly rainfall and mean monthly precipitation.

Table 5.9: Results of Regression of Rainfall on Mean Monthly Flow (0.05 Significance Level)

VARIABLE	REGRESSION EQUATION	CORRELATION COEFFICIENT
Rhodes Police mean monthly rainfall on D1H011 mean monthly flow	Y = 602.6 + 1.97 X	0.77
Malpas mean monthly rainfall on D1H011 mean monthly flow	Y = 42.6 + 0.28 X	0.75
Funnystone mean monthly rainfall on D1H011 mean monthly flow	Y = 53.8 + 0.32 X	0.78
Barkly East mean monthly rainfall on D1h011 mean monthly flow	Y = 40.85 + 0.21 X	0.72

Figure 5.11: Relationship Between Mean Monthly Flow and Mean Monthly Precipitation



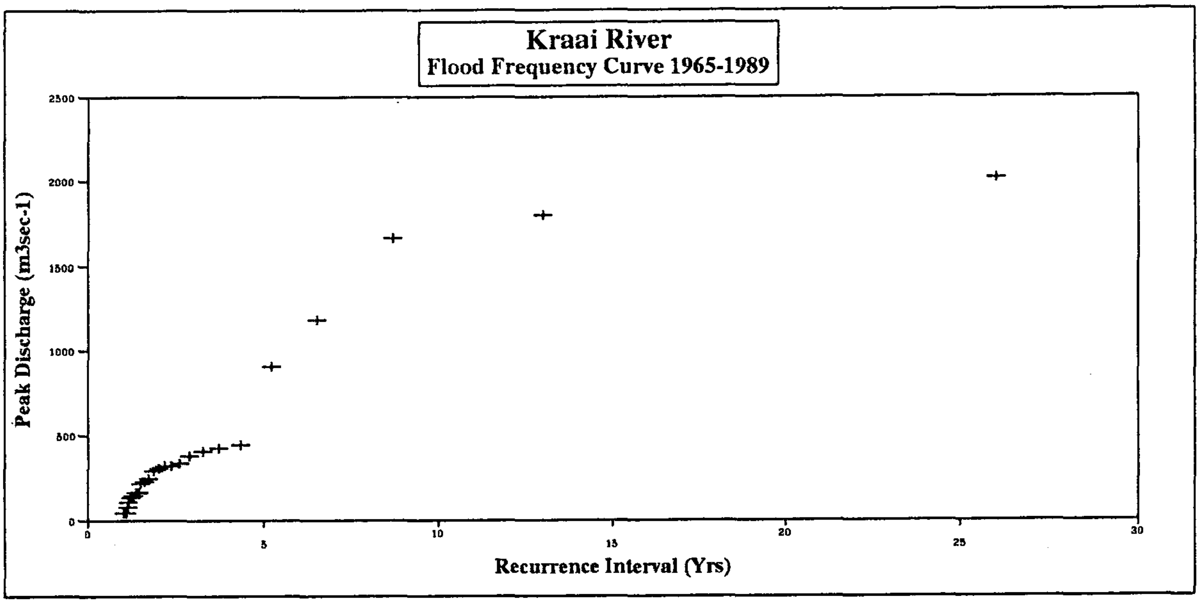
The flood frequency curve calculated for the flow data is presented in Figure 5.12. Table 5.10 displays the information in tabular form.

Table 5.10: Annual Peak Floods, Kraai River

DATE	PEAK FLOW (m^3sec^{-1})	RANK	RECURRENCE INTERVAL
1972	2016	1	26.00
1988	1797	2	13.00
1987	1665	3	8.67
1976	1186	4	6.50
1974	904	5	5.20
1989	441	6	4.33
1967	424	7	3.71
1982	406	8	3.25
1970	382	9	2.89
1978	333	10	2.60
1985	318	11	2.36
1986	317	12	2.17
1971	307	13	2.00
1979	292	14	1.86
1981	244	15	1.73
1975	224	16	1.63
1966	214	17	1.53
1969	165	18	1.44
1984	161	19	1.37
1965	146	20	1.30
1980	132	21	1.24
1977	108	22	1.18
1968	73	23	1.13
1973	40	24	1.08
1983	38	25	1.04

The results show that there is a close correlation between rainfall experienced in the Bell river catchment and the flow pattern of the Kraai River. It would follow that the magnitude and frequency of rainfall events mirrors the magnitude and frequency of the flow events. Thus a rainfall peak in 1974 is accompanied by a flow peak in 1974, and low rainfall period of 1984 is accompanied by a low flow in 1984. This would also suggest that discharge prior to 1966 would have been correlated to rainfall, assuming stable catchment conditions. It can be concluded that regional flow fluctuations mirror rainfall fluctuations in the Bell river catchment. It is likely, therefore, that regional flow variations in the Kraai river reflect flow variations in the Bell river.

Figure 5.12: Flood Frequency Curve, Kraai River



Analysis of regional flow records show peak discharges of up to 2016 cubic metres per second (cumecs) (February 1972) (Table 5.11). The mean annual flood calculated from the flood frequency curve is approximately 300 cumecs (R.I. = 2.33 yrs) (Figure 5.12). Pitman *et al* (1981) pp. 4.9 has indicated that the Bell river catchment generates approximately 25-30% of the flow measured at D1h011. This would put the bankfull discharge estimate in the Bell river in the range of 75 to 90 cumecs.

The major flood events (500+ cumecs) recorded in the Kraai river since 1965 are given in Table 5.11. It has been shown that the variation of discharge in the Kraai river is consistent with the variation in rainfall in the Bell river catchment (see Figure 5.11). The flood peaks experienced in the Kraai river should therefore also be simultaneously experienced in the Bell river.

Table 5.11: Flood Peaks in the Kraai River Above 500 Cubic Metres Per Second (1965-1989)

DATE	PEAK DISCHARGE ($m3sec^{-1}$)
February 1972	2016
March 1974	904
February 1976	582
March 1976	1186
September 1987	1094
October 1987	1665
February 1988	1797
April 1988	518

From aerial photography work and field surveys (Chapter 1), it has been shown that major channel straightening has occurred between 1969 and 1975. Further channel straightening occurred in 1988. Rainfall and discharge data (Figure 5.3 and 5.10) have shown that major rainfall and flood events occurred in 1972, 1974 and 1976. These occurred after a sustained period of below average rainfall (see Figure 5.6), referred to as Drought Dominated Regime (DDR) by Warner (1987). Personal communication with farmers indicated that major channel adjustment occurred in 1974, primarily in response to a series of floods experienced in the catchment. Further high rainfall and discharges in 1976 may have changed the channel of the Bell river from a state of dependence to a state of independence as mentioned by Newson and Macklin (1990).

The Drought Dominated Regime of the early 1980s (Figure 5.6) was again broken by a series of high rainfall and flow events from 1987 (Table 5.11). Again, after a sustained period of low rainfall, high rain and discharge events were responsible for further channel straightening in 1988 (see Chapter 1). It would appear from the evidence presented that high precipitation and therefore high flow events may be responsible for the exceedence of thresholds of channel stability with attendant channel straightening.

This conclusion relates to the whole concept of dominant discharge, thresholds and channel equilibrium. The full implications of this will be discussed in Chapter 7.

5.12 CONCLUSION

The evidence presented in this chapter has indicated the following:

a) No long term progressive trend exists in the annual rainfall series for the Bell river catchment, concurring with work by previous authors (Dyer, 1982; Tyson, 1986; Vogel, 1988).

b) No long term progressive trend exists in the seasonal rainfall series for the Bell river catchment.

c) Distinct wet and dry cycles are apparent from the data, with peaks every 16 to 19 years.

d) Wet cycles are the result of an increase in the frequency of daily events rather than the magnitude of the events, but greater magnitude events occur during wet periods.

e) Discharge variations in the Kraai river are strongly correlated to upper catchment rainfall.

f) Coincidence of peak flows and channel straightening has been noted.

The implications of these findings on the Bell river catchment are as follows; firstly, the absence of a progressive climatic trend eliminates a variable (climatic change) that may have been responsible for triggering channel instability. Secondly, the relationship between wet and dry cycles of rainfall, together with the magnitude and frequency of the events, play an important role in the hydrological response of the catchment and channel in terms of the runoff response of the catchment and the precipitation/vegetation erosion interaction, and discharge, flow competence, stream power, stability thresholds, and therefore channel instability.

CHAPTER 6

LAND MANAGEMENT AND SEDIMENT SOURCES IN THE BELL RIVER CATCHMENT

6.1 INTRODUCTION

The theoretical review (Chapter 2) has shown that not only might a changing climate be an important factor in initiating channel instability, but so too can a change in catchment land-use and management. Catchment land-use and management factors influence the hydraulic and sediment processes of a catchment (Bode, 1991), which are important determinants of channel form and pattern (Lewin *et al*, 1988). Debano and Schmidt (1989) have shown the delicate interrelationship that exists between catchment hydrology, soil erosion and catchment condition, as affected by grazing management and related activities. This chapter will attempt to describe whether catchment land-use, management and temporal changes in soil erosion in the Bell river catchment have increased sediment production to the channel. A review of the effect of catchment land-use and management on altering the hydraulic and sediment processes in catchments will also be undertaken.

An increase in catchment erosion and runoff will result in increased sediment load to the channel with it's concomitant effects such as downstream aggradation of the channel and increased flood peaks and frequency (Meade, 1983; Schumm *et al* 1984).

6.2 AIMS AND OBJECTIVES

6.2.1 Aims

a) To determine whether there has been a temporal change in sediment production to the Bell river in the medium term.

b) To determine whether sediment production in the catchment can be related to a change in catchment land-use and management, since permanent white occupation.

6.2.2 Objectives

In order to achieve these aims, the following objectives have been identified:

a) Map temporal changes in soil erosion in the catchment through the use of aerial photographs.

b) Estimate the length, areal extent and volume of erosion in the Bell river catchment through field surveys and aerial photograph work.

c) Determine temporal changes in stock numbers for the Barkly East magisterial district.

d) Determine recommended stocking rate for the Barkly East magisterial district.

e) Determine changes in land-use and management through archival searches and questionnaire surveys of farmers and the local agricultural extension officer. Personal interviews with relevant people involved in land-use and management of the Bell river catchment were also deemed appropriate.

6.3 THEORETICAL REVIEW

6.3.1 Anthropogenic Influences and Soil Erosion

Although soil erosion is a natural process, there are a number of activities associated with man which can significantly accelerate soil erosion either indirectly or directly. Even though there is irrefutable evidence that anthropogenic influences accelerate soil erosion (Stocking, 1978) and consequently have serious environmental and economic implications, very little information exists to show the significance of temporal changes in soil erosion (Garland and Broderick, 1991).

6.3.2 Effects of Grazing and Land Management on Soil Erosion and Hydrological Processes

There is extensive literature dealing with the effects of grazing and land-use management on erosion and the hydrological processes of a catchment (Smith, 1982). In the United States, the initiation of erosion in the form of gulleys and deep channel incision in the eastern and mid-eastern United States, following the conversion of natural vegetation cover to crops, is well documented (Schumm *et al* 1984).

Thorne (1991) makes the point that many streams in central Mississippi experiencing channel instability, are a result of increased sediment production from cultivation of marginal lands, leading to soil erosion through sheet and gully erosion. Clifton (1989) showed that grazing management was one of the variables affecting channel morphology. Newson and Robinson (1983), stress that land management has important hydrological consequences, a good example of this being it's effect on runoff in the catchment.

The conversion of a natural prairie catchment in Wisconsin, to agricultural land in the 1830s was accompanied by increased flooding, erosion and sedimentation (Knox, 1977). In the Rio Grande catchment (Rich and Reynolds, 1963), improper grazing was found to have increased flash floods, resulting in accelerated erosion and channel siltation. In Colorado, Graf (1979), found that vegetation distribution and characteristics played an important part in the spatial distribution of arroyos.

Sharp *et al* (1964), from studies in Cottonwood, South Dakota, showed that runoff and erosion increases markedly with increased grazing pressure. From studies on ranges that have been subjected to light, moderate and heavy grazing, they concluded that heavy grazing produces 10 times the amount of runoff as light grazing.

Stocking (1983) found that in Rhodesia (now Zimbabwe) a great deal of severe erosion could be accounted for by the effects of mans' agricultural practices through either livestock management or cropping. Eyles (in Prosser 1991), states that most valleys in the southern tablelands of New South Wales, Australia, contain gulleys up to 10 metres deep. The present gully systems have only developed since the time of European settlement in the 1830s. Gully erosion had spread to most of the region by 1910. Sequential air photos show the present gully network had completely developed by 1944. The most significant recent changes to the system was widening and deepening. Up to 50 metres of lateral erosion had occurred between 1944 and 1976. At present, the gully systems have stabilized. The recent gully incision was thus ascribed to human impact on land-use. It was stressed however, that there had been previous periods of gully incision and infilling, resulting from an extrinsic variable (climatic change), but that the recent incision was ascribed to anthropogenic influence.

A good grazing strategy will lead to less runoff and consequently less erosion (Dunford, 1954; Orr, 1975). Martin and Rich (1948) found that maximum amounts of sediment free water are produced from areas where there was a good ground cover. The good management of grazing can decrease surface runoff and consequently erosion, and increase the infiltration capacity of the soil (Rauzi and Hanson, 1966). This in turn promotes vegetation growth, further reducing erosion. Leithead (1959) found that well managed rangelands absorb moisture five to six times faster than overgrazed rangelands.

It is clear that a delicate state of equilibrium exists between the vegetative cover, surface runoff and sediment yield (Robinson, 1986). Disequilibrium may be the result of a climatic change or a response to the activities of man (Ferguson *et al*, 1991). Grazing also affects nutrient cycles and soil moisture patterns. This has important implications for the Bell river catchment. Good grazing management in the catchment will lead to increased soil moisture infiltration, lower runoff rates and consequently less erosion. Bad grazing management will result in decreased soil moisture, a lowering of the water table, increased runoff and attendant accelerated erosion.

Although there is general agreement that man has a major impact on gully erosion, quantitative evidence is lacking (Stocking, 1978; Weaver, 1988; Dardis *et al*, 1988b; Overland and Klleberg, 1991 and Garland and Broderick, 1991). Stocking (1978), studying gully erosion in the Umsweswe region in central Rhodesia found that contrary to popular theory, no evidence could be found to suggest that human influence resulted in gully incision. Rather, the gulleys were a natural response to changing environmental conditions.

6.3.3 Southern African Experience

In southern Africa, many researchers have looked at the problem of accelerated soil erosion (Stocking and Ellwell, 1976). Beckedahl and Dardis (1988), state that in southern Africa soil systems exist within finely balanced states of dynamic equilibrium. Years of over-utilization of the veld (natural vegetation) has led to it's deterioration (Snyman and Van Rensburg, 1986) in terms of plant cover and diversity of species, which in turn has accelerated soil erosion (Scott, 1988).

Pentz (in Scott 1988), showed the close relationship that existed between erosion and land-use. He stated that erosion in certain parts of South Africa is directly related to land-use. Weaver (1988), working in the Ciskei, found that land-use had the greatest influence on soil erosion. Snyman and Van Rensburg (1986), studying the Free State grassland communities, found that the lowest runoff occurred on climax vegetation areas, and the highest runoff on a medium slope with pioneer vegetation. Similarly, highest soil loss occurred in pioneer grass species, and lowest soil loss occurred from climax species. Bosch (1989) stressed the importance of correct grazing strategies to obtain the best species diversity in South African grasslands.

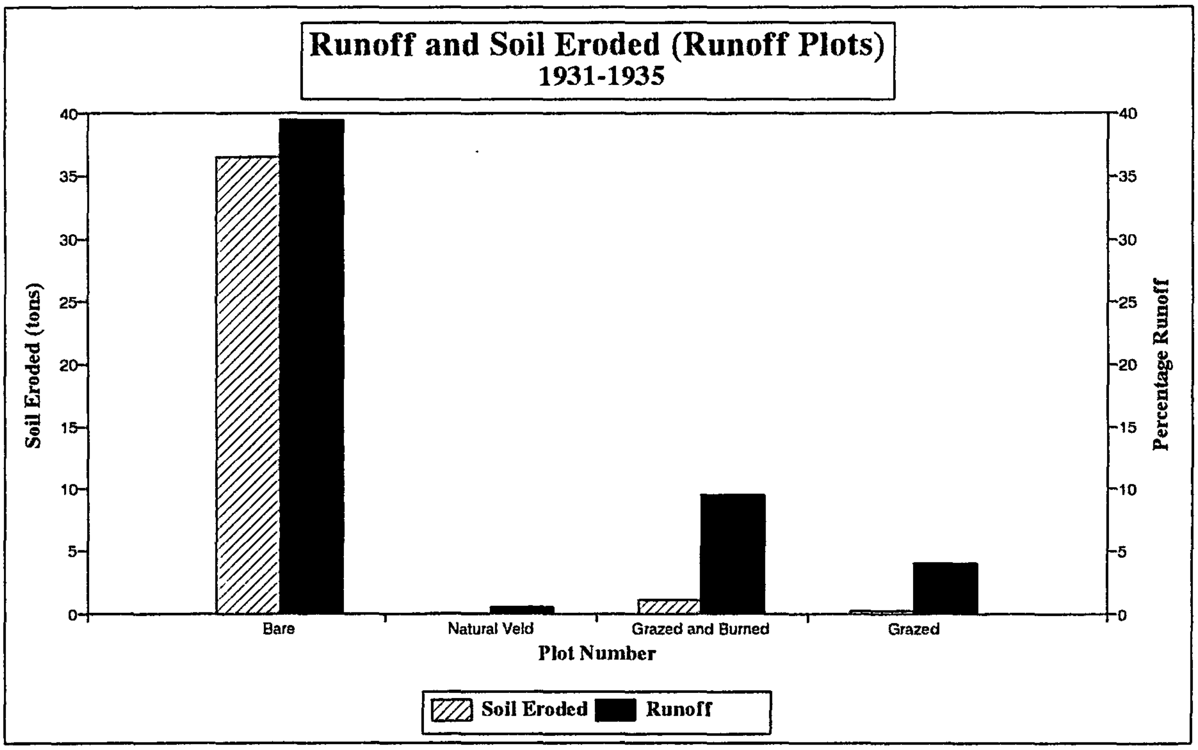
Bode (1991) has shown from work on runoff plots from the Dohne Sourveld region of South Africa that, after veld grazing and burning, soil and runoff increase substantially. Greatest losses occur from plots that are annually burnt and continuously grazed, whereas biennially burnt rotational grazing plots showed significantly smaller losses. Furthermore, soil loss and runoff increased from badly managed veld even though rainfall did not, indicating that the effect of bad management practices become more pronounced with time.

Bode (1991) confirmed earlier work by Thompson (1935), who using runoff plots showed that burning, crop cultivation and fallow ground, increases the amount of runoff and soil loss. Conservative grazing minimized soil and runoff loss, while overgrazing was found to severely increase runoff and soil erosion (see Figure 6.1).

Other factors that have effected soil erosion in southern Africa include population pressure (Marker, 1988) and change in urban land-use (Rowntree *et al*, 1991). Shakesby and Whitlow (1991) stated that in Zimbabwe, although anthropogenic factors have clearly been identified as causative factors in land degradation on a local level, sodic soils were considered to be a crucial determinant of gully erosion.

Physical factors such as the grain composition of sediments and the presence of exchangeable cations (Na^+ K^+ Ca_2^+ and Mg^+) were stressed as important causative variables in donga erosion in the Aliwal North area (Van Rheede Van Oudtshoorn, 1988). Beckedahl and Dardis (1988) stressed the importance of culverts and soil piping in the initiation of erosion. Soil type is important in determining erosion. Watson *et al* (1984), indicated that soils of the solonetz type are especially prone to erosion on account of their low aggregate stability and amount of sodium adsorbed on the clay complex. The effect of sodium is to increase the thickness of the diffused electric table layer surrounding individual clay particles and decrease cohesion between particles thereby increasing the susceptibility to erosion.

Figure 6.1: Runoff Plots Results from Thompson (1935)



Thus, although man's influence on the catchment is recognized, it should not be seen as the singular factor affecting soil erosion. Rowntree (1988b) concurs with this viewpoint and cautions that although poor veld management in many areas has lead to soil degradation, the problem should be seen in the context of "natural environmental conditions and geomorphological processes" (Rowntree, 1988b pp. 175). The difficulty, however, is to determine:

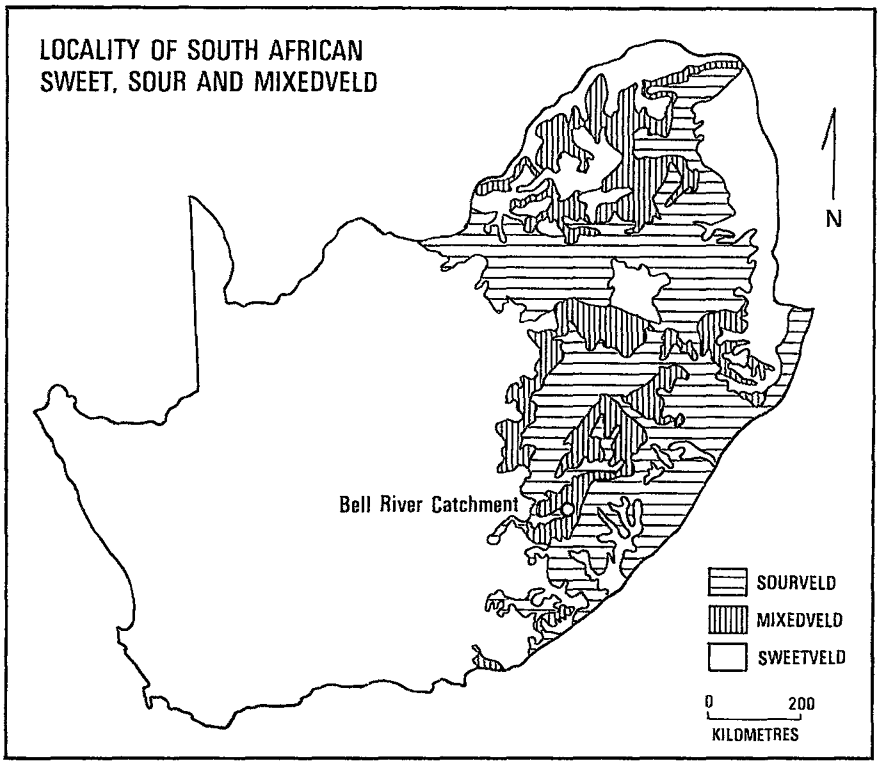
a) Which extrinsic variable is responsible for erosion initiation, and
b) If the erosion initiation is a result of interacting extrinsic variables, which one is dominant at which period.

6.4 GRAZING AND LAND-USE MANAGEMENT PRINCIPLES IN SOUTH AFRICA

Traditionally, South African grazing areas have been subdivided into three main types of veld: sweetveld, sourveld and mixed veld (Tainton, 1988). Sweetveld refers to veld that remains palatable and nutritious throughout the year when mature. Sourveld refers to veld that remains palatable only during the grazing season (usually summer). Mixed veld refers to that veld that is somewhere between the two extremes, and may vary from sweet-mixed to sour-mixed. A map showing the distribution of these veld types in South Africa is given in Figure 6.2.

The Bell river catchment can be classified as sour to mixed veld. A characteristic of this veld is that it occurs at high altitudes and cooler temperatures (Tainton, 1988).

Figure 6.2: Distribution of Veld Types in South Africa



Three main grazing strategies are used in South Africa:

a) Continuous grazing: where stock are placed in an enclosed area and not moved for the entire season

b) Rotational Grazing: where grazing for stock is subdivided into at least one more camps than there are groups of animals, this allows for the rotating and resting of camps, and

c) Zero Grazing: where the animals are denied access to direct grazing, but where forage is fed green to the animals (Tainton, 1988; Barnes, 1989).

Within each of these grazing strategies, two main types of grazing intensities have been identified:

a) High Performance Grazing (HPG) and Controlled Selective Grazing (CSG), which adopt the policy of lenient use of the veld, and

b) High Utilisation Grazing (HUG) and Non Selective Grazing (NSG) which adopt the policy of heavy utilisation (Barnes, 1989).

HUG/NSG have been found to be more appropriate in humid climax vegetation communities as opposed to HPG/CSG policy which is better used in arid climax communities. Depending on the efficiency and appropriateness of the grazing type and strategy, vegetation and soil degradation can be avoided (Stuart-Hill, 1989). It is only the overuse and inappropriate use of veld that leads to environmental degradation (Teague, 1989).

Of importance to good veld management and grazing strategy is the determination of veld carrying capacity and stocking rates. Stocking rate is defined as the total number of stock per unit area, expressed per length of grazing period per year (Danckwerts, 1989). Whether an area is overstocked or not depends on the carrying capacity of the veld. Carrying capacity (Tainton, 1988) is defined as the area of grazing land and pastures required to maintain an animal unit in good productive condition for a year without vegetation or soil degradation. It is usually expressed as hectare/animal unit/year.

Although overstocking has been shown to result in veld degradation and soil erosion and financial decline in the long-term (Danckwerts, 1989), many South African farms are overstocked, since overstocking can produce immediate short-term financial gain. Danckwerts (1989) has shown that although not often practised by South African farmers, conservative stocking rates increase veld resilience towards drought. It can also increase long term productivity and produce maximum profitability. Short-term gain philosophy has ignored scientific advice and resulted in veld and soil degradation in many parts of South Africa.

6.4.1 Burning as a Veld Management Tool

Veld burning is an important part of the African environment (Trollope, 1989) and has been used extensively by agriculturalists for centuries as a veld management tool. Veld burning serves two purposes:

a) It removes unwanted and moribund vegetation, and
b) It stops the encroachment of undesirable species (Tainton, 1981; Trollope, 1984 and 1988; Bode, 1991).

Burning must occur at the right season, this is usually just before the growing season when the soil is wet, so as to retain as much surface litter as possible to combat soil loss. However, indiscriminant burning in order to promote out-of-season growth has been responsible for veld degradation over extensive areas of South Africa and is still a problem in the NE Cape, Transkei, Natal and the Transvaal highveld. Out of season burning not only reduces the strength of the grass sward, but increases runoff and soil erosion (Danckwerts and Teague, 1989; Trollope, 1989; Bode, 1991).

In order to relate land management to temporal changes in soil erosion, it was necessary to map temporal changes in soil erosion. Soil erosion mapping was undertaken for the Bell river catchment. It was thus necessary to determine what soil erosion mapping techniques would be most appropriate for the task.

6.5 SOIL EROSION MAPPING TECHNIQUES

The literature is replete with examples of the use of aerial photography to monitor temporal changes in soil erosion (Stocking and Ellwell, 1973; Keech, 1980; Marker, 1988). Soil erosion mapping is a systematic method that can represent erosion features and their associations simply and concisely (Thwaites, 1986). Soil erosion mapping should be distinguished from erosion hazard mapping, erosion risk mapping and erosion intensity mapping, where the broad objective is to identify areas threatened by soil loss (Morgan, 1986). The approach to analyzing change in sequential survey mapping is a way then to ascertain changes in erosion density (Bode, 1986). Soil erosion mapping gives consistent and reliable results, and reduces the cost and time to produce maps (Williams and Morgan, 1976; Morgan, 1980).

The use of aerial photography is common in soil erosion mapping. Keech (1968) used aerial photography in Rhodesia to determine temporal shifts in erosion for the Mondoro Tribal Trust Land and found a progressive increase in the area under gully erosion. Nir and Klein (1974) used aerial photography in Israel to delimit gully erosion in N. Shiqma watershed. Whitlow (1986) derived a method for mapping erosion in Zimbabwe using aerial photography based on a grid sampling procedure using 1:25 000 aerial photography.

Garland and Broderick (1991) mapped soil erosion in the Tugela catchment in Natal and Kwa Zulu and through the use of sequential air photos were able conclude the following:

1) A small but significant decrease had occurred in areas affected by sheet erosion between 1944/5 and 1976/81
2) The decrease was unrelated to population density, and
3) Decreased erosion may have been the result of climatic fluctuations or improved farming techniques.

Ntsaba (1989) mapped soil erosion for a peri-urban catchment in Lesotho using black and white panchromatic aerial photographs, based on a classification recommended by SARCCUS (1981). Weaver (1988) and Marker (1988) used aerial photography to delimit areas of erosion in different parts of the Ciskei. Rowntree (1991a) used air photography to delimit drainage networks in the Baringo district in Kenya.

Welch *et al* (1984) have shown that a photogrammetric approach to mapping soil erosion can be used effectively to monitor erosion. Scale of erosion mapping is important, and often depends on the nature of the study (Weaver, 1989). Keech (1969) states that the most effective scale to use for aerial photography is 1:25 000, as smaller scales lose detail and larger scales involve a sacrifice of synoptic view. In reality, choice of scale depends on what is available.

Ground truthing of aerial photography is extremely important. Williams and Morgan (1976) recommend that the two stereo interpretations be carried out with the ground truthing between them. The importance of field surveys is stressed by Keech (1968). Garland (1982), emphasised the importance of the confident identification of erosion features, and how this can only be achieved through systematic ground truthing.

Recent technological advances have aided soil erosion mapping. Satellite imagery (Morgan, 1986) can be used as an alternate to aerial photographs with, of course, the concomitant costs. Garland (1982) shows how infra-red sensitivity aids interpretation through the identification of vegetal and moisture differences in a terrain.

The use of Geographic Information Systems (GIS) has automated the previously tedious task of transferring two or more spatial data sets to a common scale previously handled manually (Cocks and Walker, 1987). The GIS enables the integration of layers of spatially orientated data. The advantage of this system includes the ease of data retrieval, the ability to synthesize large amounts of spatial data, and the ability to account for projectional distortions (Walsh, 1985).

6.6 METHODOLOGY

A methodology was devised that would attempt to determine:

a) Whether soil erosion had increased in the catchment, with attendant sediment production increase to the channel, and

b) Whether land-use and management practices in the catchment were affecting the hydraulic and sediment processes in the catchment triggering channel form and pattern change.

6.6.1 Soil Erosion Mapping

The use of aerial photography to map erosion in the Bell river catchment is the most cost effective, objective method to monitor rates of erosion, and was therefore used to determine temporal variations in soil erosion. In order to achieve this the following criteria (based on Morgan, 1980) were identified as necessary in the survey:

1) The survey method should be simple, objective and obtain quantitative information

2) The survey method should enable rapid and inexpensive study, and

3) The survey should enable temporal monitoring of erosion for a given area

Black and white panchromatic aerial photographs were used for the sequential survey. Job 318 (1952), Job 656 (1969) and Job 731 (1975) were available for the catchment. The air photos were all taken during the winter months in each year, ensuring a similar vegetation cover. The photographs were all at different scales 1:30 000 (318), 1:20 000 (656) and 1:50 000 (731). Stereo interpretation was aided through the use of a Topcon mirror stereoscope with a 3x binocular magnification attachment.

Initially it was decided to use the classification of the South African Regional Commission for the Conservation and Utilization of the Soil (SARCCUS, 1981) to map soil erosion. After the survey of Job 318, it was apparent that the system would be inappropriate for two main reasons, namely:

1) Vegetation type (*Cymbopagan Themeda Veld* and *Themeda-Festuca Alpine Veld*) made it impossible to determine with any degree of accuracy or confidence, sheet and rill erosion. This was due to the extensive vegetation coverage of the grasslands which covered evidence of these features, and the tone reflected on the aerial photographs.

2) The scale of the photographs precluded the accurate definition of smaller erosion features such as slumps and rill erosion, a problem also experience by Garland and Broderick (1991). Keech (1980) emphasized the importance of accuracy in aerial photo work and it's dependence on scale.

The only features that could be accurately identified were incised channels and gulleys. These corresponded roughly to the G3-G5 classification of SARCCUS (1981). As it was impossible to determine the width and depth of these gulleys from the aerial photographs an alternate method of mapping was required.

The method used was similar to the methodology adopted by Keech (1969) and Garland (1982), where erosion features were simply traced onto transparent film and then transferred onto a base map. Using this system, sequential surveys were performed either side of a ground survey.

Due to the size of the catchment (424 km^2) and the mountainous terrain, it proved impossible to ground survey the entire catchment in detail. Most of the catchment (80% of the areal extent), was visited or viewed from high points. Prominent erosion features (large gulleys and incised channels) on the aerial photographs were visited and detailed observations made. In this manner a reliable and accurate representation of the aerial extent of erosion was obtained.

From the survey and measurements of the sizes of selected gulleys (Table 6.4), estimates of the volume of material produced by the gully systems was made (Table 6.5). In order to produce a margin of error/variability, estimates were calculated for different sized and shaped gulleys. Based on field experience, two shapes of gulleys were identified, V shaped gulleys and U shaped gulleys. Three sizes of gulleys were identified and classified according to size. A type 1 gully was calculated as being 2 metres wide and 2 metres deep, type 2 gully 5 metres wide and 5 metres deep and, a type 3 gully 5 metres deep and 10 metres wide. In this manner, estimates of the volume of material produced from the gully systems were calculated.

Eroded features were often found adjacent to, or dissecting, the cultivated fields. These were identified and mapped from the aerial photographs. A map showing the distribution of the cultivated area of the catchment is depicted in Figure 6.6.

The data obtained from the surveys were entered onto a GIS (ARC INFO). Through the use of this tool it was possible to measure the length of eroded features, and to present a map of the erosion for each date.

In order to determine the aerial extent of erosion in 1991, a classification system was drawn up (Table 6.1) and used to map present day erosion. Ground surveying was used to determine the features, and the results plotted onto a base map (Figure 6.6).

Table 6.1: Erosion Classification System used for Erosion Mapping in the Bell River Catchment 1991.

TYPE	APPROXIMATE SIZE	DESCRIPTION
1		Natural Unincised Channels
F	Finger Gulleys	Generally Recent Features Found on Steep Hillslopes
2	<2m deep <3m wide	Slightly Incised Channels
3	<5m deep <10m wide	Moderately Incised Channels
4	>5m deep <10m wide	Severely Incised Channels

6.6.2: Catchment Land-Use And Management

It was intended to undertake personal interviews with the farmers in the Bell river catchment, dealing with catchment land-use and management issues, but these were excluded for reasons beyond the control of the author. Postal and informal personal interviews were used which were generally less satisfactory.

Questionnaires dealing with catchment land-use and management issues were sent to the farmers (see Appendix E). Questions were asked dealing with such issues as burning and grazing regimes, stock numbers, catchment erosion and land-use management. A formal interview was conducted with the local agricultural extension officer, but much of the information required was either inaccessible or no records were available (stock numbers in the catchment for example).

None of the farmers nor the extension officer were able to supply historical stock numbers through either their non-existance, or their reticence to release them. As stock data was unavailable for the Bell river catchment, the closest reference data available was for the magisterial district of Barkly East, of which the Bell river forms a part. This was used as this was the only data available. Regional stock numbers for the district of Barkly East were obtained from the Cape Statistical Registers (1891-1981). Figures were obtained from 1891 to 1981. After 1981 the census area changed, disallowing comparison with earlier years.

A recommended stocking rate figure was obtained from the regions agricultural research unit, Dohne Agricultural Research Centre. Based on the size of the Barkly East magisterial district (3644 km^2) and the recommended stocking rate (6.5 hectares per large stock unit) it was possible to calculate the recommended stocking density (carrying capacity) for the district, and therefore determine whether the Barkly East region was, on average, overstocked.

Archival searches were undertaken at the Cape archives in Cape Town to ascertain whether any information existed relating to historical catchment land-use and management. No information could be found apart from farm boundary information obtained from old maps. To determine whether there had been a change in farm size, farm boundary maps were obtained for 1898 and 1990. Based on evidence from these maps, it was possible to determine that there has been no change in the position of the farm boundaries for the last 92 years. Personal communication with farmers and relevant authorities, however, indicated that there had been a shift in the number of resident farm owners.

6.7 RESULTS

6.7.1 Catchment Erosion

The erosion maps produced from Jobs 318, 656 and 731 are presented in Figures 6.3 to 6.5. Table 6.2 presents the length of eroded features, in kilometres, for the sequential dates. Plates 6.1 and 6.2 give an indication of the size of selected gulleys in the catchment.

Table 6.2: Incised Channels and Gulleys, Total Length

DATE	ERODED LENGTH (km)	INCREASE IN LENGTH (km)
1952	33.29	
1969	40.50	7.21
1975	47.70	7.20

Erosion has clearly increased in the catchment since 1952. An increase in length of gulleys of sixty-nine percent was recorded over the 23 year period. The diagrams (Figure 6.3 to 6.5) indicate how most of the erosion increase has been in the middle and lower sections of the catchment where there are deep colluvial soils. Many of the major gulleys on the south facing slopes produce generally coarse material with a greater heterogeneity (boulders, cobbles, gravels and sand). Large gulleys also occur on the north facing slopes and also produce significant quantities of material. This tends to be relatively fine material such as sands and silts. This increase means that significant quantities of sediment have been injected into the Bell river. This material often forms small alluvial fans at the base of the gulley systems (See Plate 6.3). These are significant sediment sources and storage zones and become mobilized in medium to high flows.

Plate 6.1: Gully Erosion, Bell River Catchment

Plate 6.2: Gully Erosion, Bell River Catchment

Plate 6.3: Alluvial Fan, Bell River Catchment

The ground surveyed map for erosion for 1991 is presented in Figure 6.6. Table 6.3 presents the lengths of gulley systems for 1991. Even though the classification used to determine the erosion in 1991 is not directly comparable to the survey of aerial photography, it is clear that there are still significant, active gulleys in the catchment producing sediment for the channel.

Table 6.3: Length of Eroded Features, 1991

EROSION CLASS	ERODED LENGTH (km)
F	8.47
2	37.04
3	61.44
4	15.24

The results and measurements of the four gulleys selected for analysis are presented in Table 6.4. The position of these gulleys in the catchment is shown in Figure 6.5. Using these results as an indication of the average size of gulleys, estimates of the volume of material produced by the gully systems was calculated (Table 6.5). Clearly, significant volumes of material have been produced by these gully systems, this has important implications for channel instability. Morgan (1986) has stated that gulleys are always a sign of landscape instability.

The land in the catchment is well fenced with some of these fences stretching across deep gulleys (see Plates 6.4 to 6.6), leaving fence poles suspended in mid-air. Some of these fence poles still have soil attached to them which indicates that they were previously embedded in the ground. From this evidence, it was concluded that for those particular gully systems, gully initiation occurred after fencing. If the date of fencing could be determined, then it would be possible to determine a maximum date of gully incision.

Interviews with farmers ascertained that fencing was started in the early 1900s and continued until the 1970s by which date most of the farms had been fenced. Gulleys may have existed before this time but major incision must have taken place within the last 90 years.

Figure 6.3: Catchment Erosion, 1952

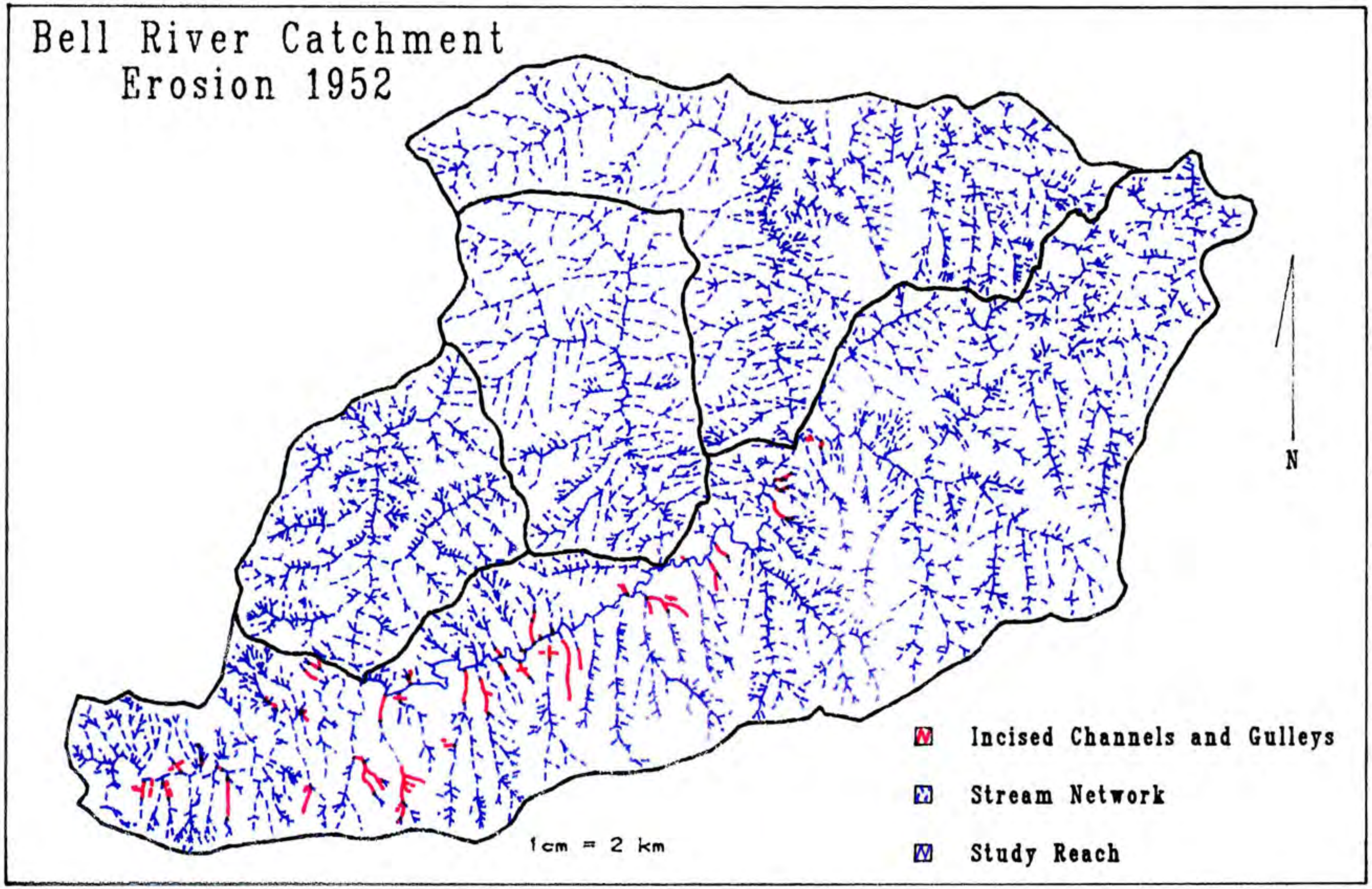


Figure 6.4: Catchment Erosion, 1969

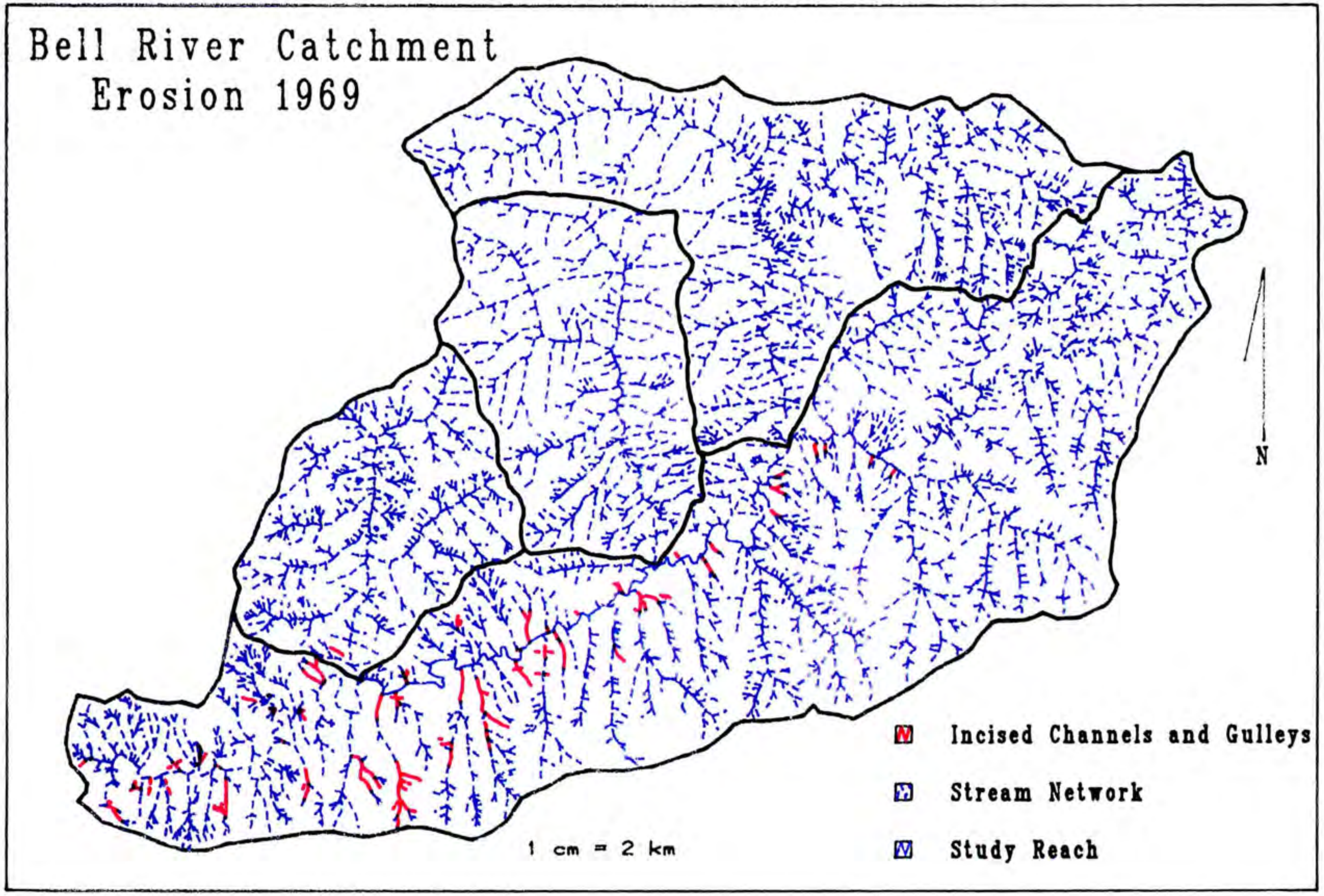


Figure 6.5: Catchment Erosion, 1975

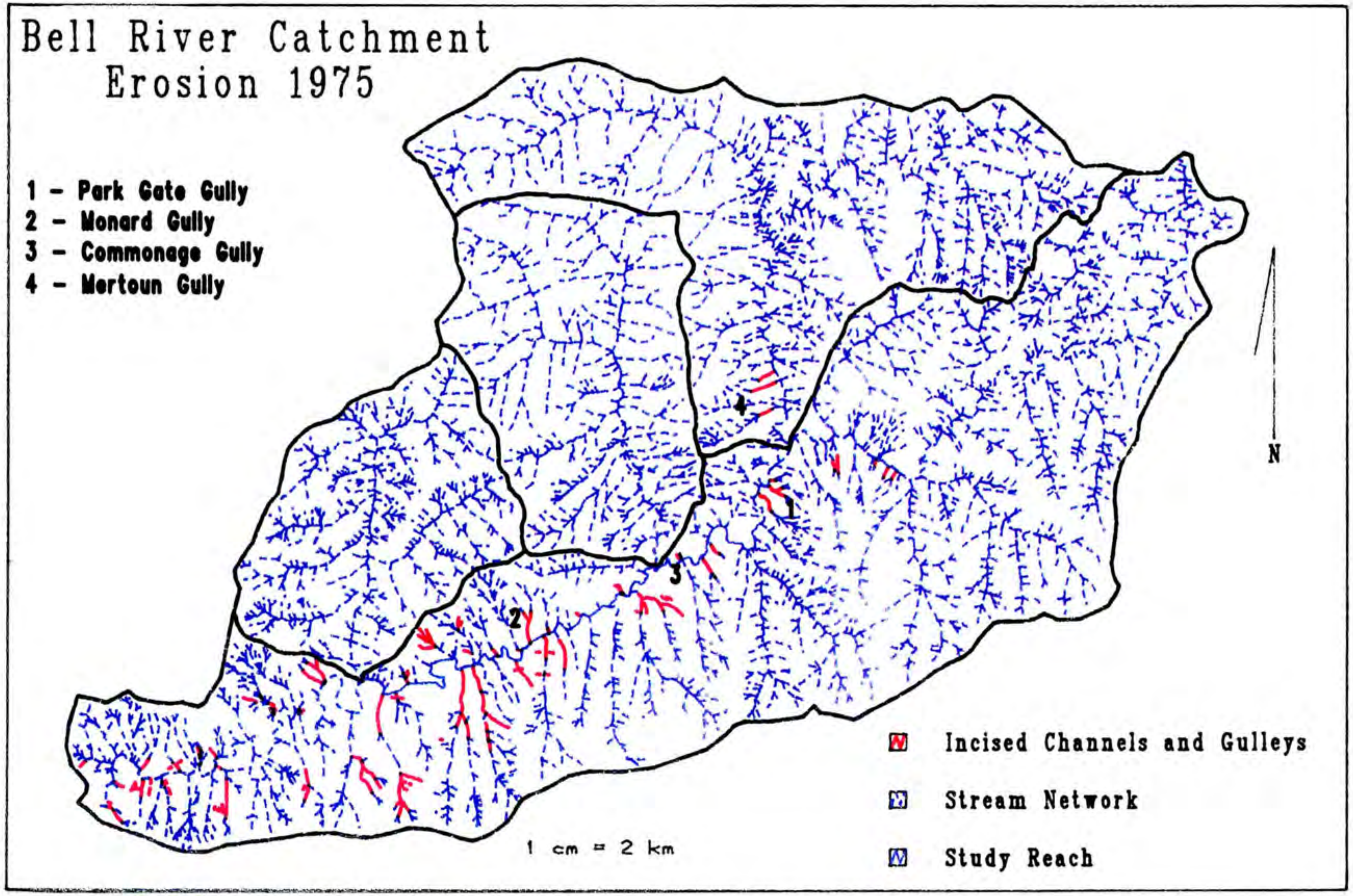


Figure 6.6: Catchment Erosion, 1991

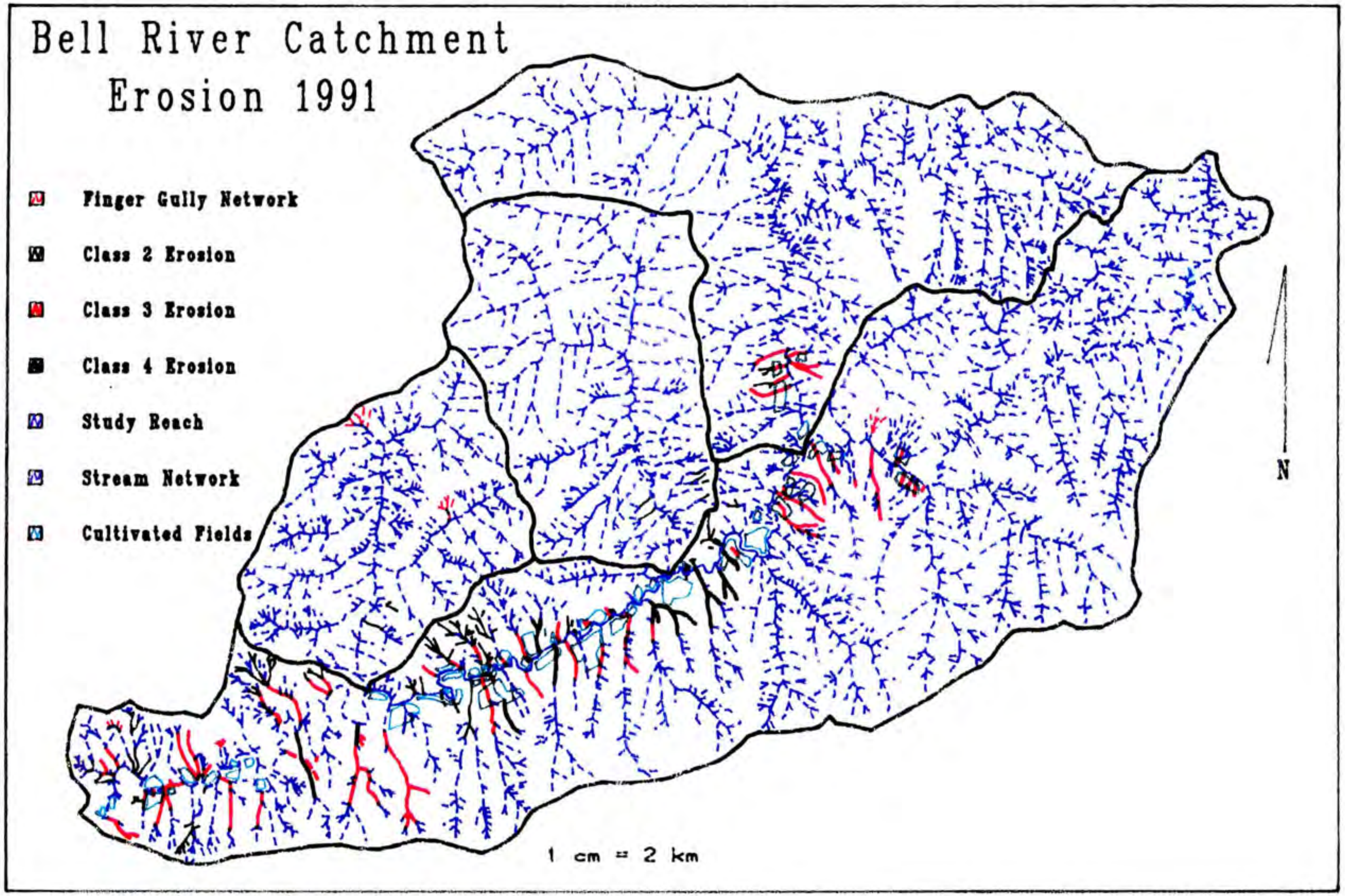


Table 6.4: Sizes of Selected Gulleys, Bell River Catchment (See Figure 6.5)

GULLY SITE	POSITION	TOP WIDTH (m)	DEPTH (m)	BOTTOM WIDTH (m)	ASPECT
Park Gate	Top	14.8	13.1	9.3	North
	Bottom	7.2	3.3	5.3	
Monard	Top	3.0	3.8	1.5	South
	Midslope	21.5	9.5	15.0	
	Bottom	10.4	5.1	7.7	
Commonage	Top	5.8	3.6	2.70	North
	Midslope	5.30	2.20	4.50	
	Bottom	16.3	8.0	7.8	
Mertoun	Midslope	7.0	3.3	3.8	South

Table 6.5: Estimates of Volume of Material (Cubic Metres) Produced for the Bell River Gully systems

DATE	1952	1969	1975	1991
Classification		V-Shaped Gully		
Type 1 (Total)	66580	80990	95400	
Type 2 (Total)	416125	506188	596250	
Type 3 (Total)	832250	1012375	1192500	
Class 2				111135
Class 3				645120
Class 4				38100
Total				794355
Classification		U-Shaped Gully		
Type 1 (Total)	133160	161980	190800	
Type 2 (Total)	832250	1012375	1192500	
Type 3 (Total)	1664500	2024750	2385000	
Class 2				222770
Class 3				1397760
Class 4				762000
Total				2382530

Plate 6.4: Suspended Fence Pole, Park Gate Gully, Bell River Catchment

Plate 6.5: Suspended Fence Pole, Buttermead Gully, Bell River Catchment

Plate 6.6: Suspended Fence Pole Showing Remnants of Soil, Bell River Catchment

6.7.2 Land-Use and Management

6.7.2.1 Stocking Rates

The stock numbers obtained for the Barkly East district are displayed in Figure 6.7. The recommended stocking rate of 6.5 ha per Large Stock Unit (LSU), was used to calculate the recommended stocking rate for the Barkly East district (3644 square kilometres). Figure 6.8 is a plot of the information. The recommended stocking rate calculated for the Barkly East magisterial district is 56 081 large stock units. Total stocking rates reached their peak in the early 1920s (140 000 large stock units) and have declined steadily since then. Even though stocking rates have declined, the district was still overstocked in 1981 (Figure 6.8). The district has thus experienced more than a century of overstocking. This would indicate severe land degradation.

6.7.2.2 Questionnaire Responses

Of the 15 questionnaires sent out, only 4 were returned. Although this represents an 27% response rate, significant statistical analysis of the data would not be appropriate given the small sample size. The results of the questionnaires will be discussed in terms of questionnaire response trends, together with personal interviews with farmers.

Figure 6.7: Stock Numbers, Barkly East Magisterial District (Figures Obtained from Cape Statistical Registers, See Reference List)

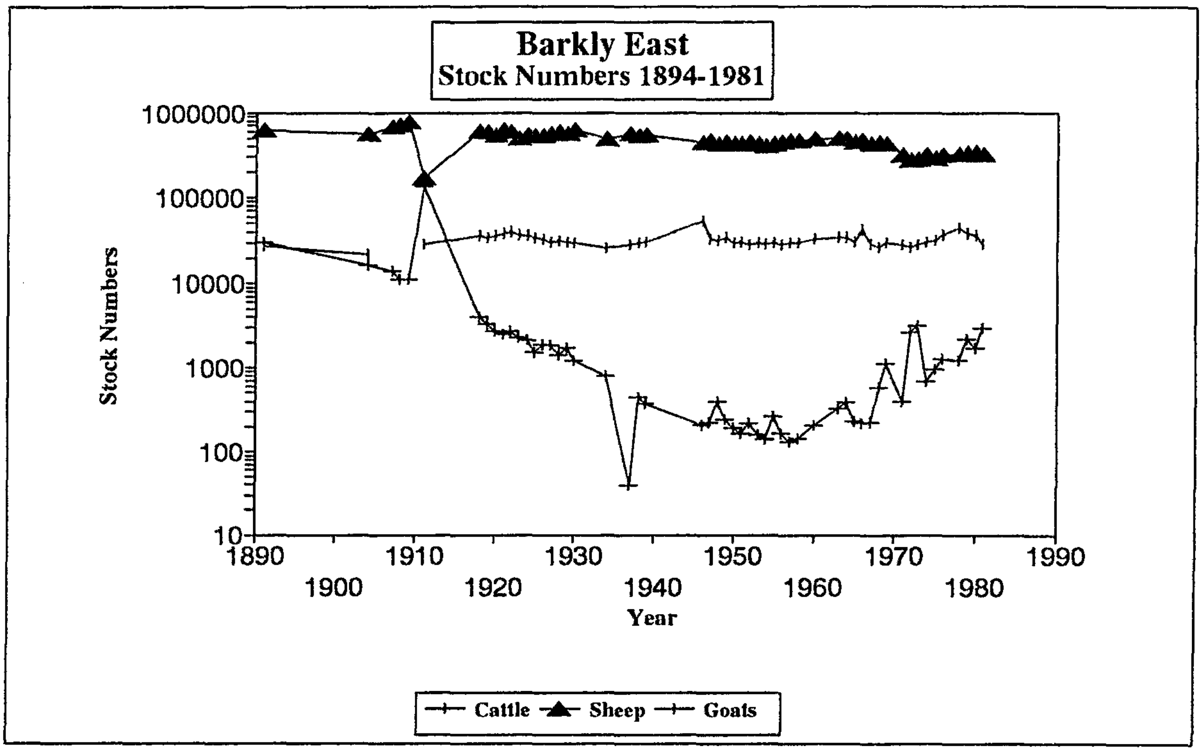
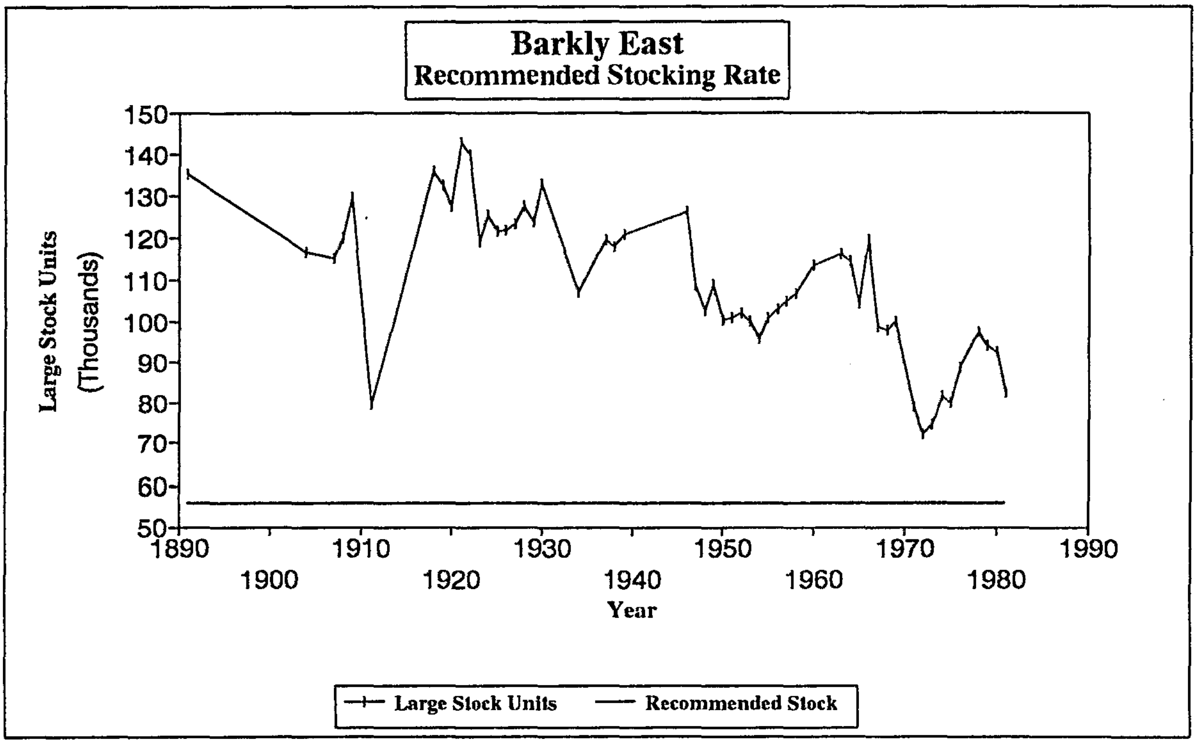


Figure 6.8: Recommended Stocking Rate, Barkly East Magisterial District



A number of the farmers in the district each own between three to six farms in the catchment and many own farms in other parts of the district. The grazing management system is based on a rotational grazing scheme both within a single farm unit and between farm units. Not only are the stock rotated within each farm unit, but stock are moved from farm to farm depending on the season. Stock are also, in some instances, moved out of the catchment during the summer to lower altitude farms in adjoining catchments. A HUG/NSG grazing scheme is adopted by the farmers as recommended by Tainton (1988) for climax grassveld.

There is general consensus among the farmers and the extension officer that veld condition and the erosion status of the catchment has improved during the past 30 years (an improvement in the veld condition refers to an increase in the number of palatable species per unit area as well as an improvement in vegetal basal cover). This has been attributed to three main factors:

a) Stock numbers have declined in the last 30 years (confirmed by the regional trend (Figure 6.7)).
b) Better veld management, as farmers are becoming increasingly conservation conscious, with modern, appropriate scientifically based grazing strategies being applied, and
c) Previously farmers in the catchment owned 1 or 2 farm units that were overstocked and overgrazed, this led to veld degradation and soil erosion. Presently most farmers own 3 to 6 farms, enabling a conservation conscious farming philosophy, while still running a financially viable enterprise.

Veld burning occurred approximately every 4 years. This appears to be the general trend, although one farmer mentioned he had only burnt once in the last 72 years. No evidence is available to make any inferences about the effect of burning on soil erosion in the Bell river catchment.

6.8 DISCUSSION OF RESULTS

Due to the nature of the evidence collected in this chapter, it is important to distinguish between hard evidence, reasonable evidence and speculation. The discussion of results will attempt to clarify this position. The evidence presented from the sequential air photo surveys indicates that there has been significant erosion in the catchment. From 1952 to 1975 the length of eroded features (gulleys and incised channels) had increased by 14.4 kilometres. The fact that 33.29 kilometres of eroded features existed in 1952 indicates that severe incision must have occurred before that date. Not only are gully erosion and channel incision evident, but from the ground truthing it was clear that significant sheet erosion occurred, and is important in terms of sediment production to the channel. Unfortunately, the grass cover obscured all evidence of this on the aerial photographs, and thus no quantitative measurement could be made.

It should be noted that deep gulleys are often found adjacent to, or in cultivated fields. Aerial survey work showed that by 1952, cultivation of the floodplain and lower colluvial foot slopes had fully developed. Three possible conclusions can be drawn from this:

a) Cultivated fields on the floodplain have caused significant gully erosion, or

b) Cultivated fields and deep gulleys are coincidental, as both occupy areas of deep soil, or

c) Increased runoff from upland areas, due to land-use changes, have increased the potential for this form of (gully) erosion.

The resolution of this issue is outside the scope of this research; what is salient here is that there has been significant erosion of the lower slopes and that this has produced significant quantities of coarse and fine material for the channel.

The evidence begs the question whether or not the origin of the eroded features is recent, as the date of incision has important implications for channel dynamics. Recent accelerated erosion will have led to large volumes of material being inputed into the channel during the last 90 years, which would result in the disruption of channel equilibrium. If the erosion features were older and represented cyclical periods of infilling and incision, then most of the sediment would have been injected into the channel over a longer period, resulting in the channel equilibrating to the increased load. This would result in a very different channel response.

To state that the eroded features in the Bell river catchment are recent features requires evidence.

Figure 6.7 shows how the stocking density of the Barkly East district (of which the Bell river catchment forms part) has declined during the last 90 years. Farm boundaries have remained stable. The agricultural extension officer states that stock numbers in the catchment have declined by about 300 percent in the last 100 years. Figure 6.8 indicates the recommended stocking rate for the region, as given by the agricultural research centre. Based on this figure the Barkly East district is still overstocked even though the stock numbers have declined significantly. This is despite the fact that it widely accepted that overgrazing and overstocking results in significant increases in water and sediment yield. Overstocking and accelerated erosion in the catchment have been shown to be coincidental.

It is interesting to note that the maximum rate of stocking (during the 1920s) coincided with the end of a long dry period (see Figure 5.6). The late 1920s were much wetter, but stock numbers fell slightly. This could imply conditions for significant erosion following veld degradation. After this period, stock numbers declined progressively and appears to bear a relationship to wet and dry periods, with periods of high rainfall associated with higher stocking rates, and periods of low rainfall with declining stocking rates.

Questionnaire responses and personal communication with the farmers and the extension officer confirmed that stock numbers in the Bell river catchment mirror the regional trends. The veld condition has improved both in terms of the number of palatable species and the percentage grass cover. This is due mainly to the introduction of rotational grazing schemes, fenced camps and improved farm ownership to farm unit ratios.

The evidence presented indicates three things: firstly, significant erosion has occurred in the catchment in the last 90 years and this has led to significant sediment production to the channel, secondly, regional overstocking has occurred, and lastly, the literature presents strong evidence for a relationship between overstocking, poor veld management and accelerated erosion. However, it should be **stressed** that no causal link can be shown between overstocking and erosion. From the evidence presented and according to contemporary literature, it may be inferred or suggested that this could be the case.

6.9 CONCLUSION

It is possible, based on the evidence collected, to suggest the following:

1) Land degradation, Overstocking and poor veld management practices have been practised in the Bell river catchment, leading to land degradation.

2) Due to declining stock numbers and better veld management, catchment condition has improved in terms of grass cover and percentage of palatable species.

3) Accelerated erosion initiation in the catchment was probably the result of overstocking and poor veld management following white occupation. Many of the deeply incised channels and gulleys dissecting the land are a result of former catchment mismanagement.

4) Significant amounts of sediment have been injected into the Bell river channel during the past 90 years.

CHAPTER 7

DISCUSSION SUMMARY

7.1 INTRODUCTION

The aim of this chapter is to synthesize the information from the previous chapters in an attempt to identify the major causes of channel form and pattern change in the Bell river. Channel straightening, steepening and meander cutoffs have changed sections of the Bell river from a meandering to a straighter, braided channel (Chapter 4). Braided stretches are associated with channel widening, relatively larger bed material and general instability. Braiding is often a response to an increased volume of bed material (Chapter 2). Two sets of variables have been identified as affecting the potential for channel change in the Bell river, namely: spatial and temporal controls.

It has been noted previously that while spatial control variables affect the potential for local channel change, temporal control variables may initiate local and downstream changes in spatial controls causing channel instability. The following discussion will provide a summary of the spatial and temporal control variables in the Bell river and discuss the possible causes of channel instability.

7.2.1 SPATIAL CONTROLS ON CHANNEL FORM

Chapter 4 has indicated that the two primary spatial controls determining channel form and pattern are riparian vegetation and bed material size. Riparian vegetation stabilizes the channel perimeter resulting in narrow confined channels, bank accretion and reduced channel cross-sectional area. Flows smaller than bankfull discharge are confined within stable banks. Reduction in cross-sectional area increases the potential for more frequent flooding. Riparian vegetation in the Bell river may therefore be said to have two main effects, depending on flow conditions, namely:

a) At flows less than bankfull, riparian vegetation increases bank stability and causes bank accretion with attendant reduction in cross-sectional area, or

b) At flows greater than bankfull, reduced channel capacity results in more frequent flooding and out of bank scour, which may ultimately lead to channel avulsion.

Bed material calibre is an important determinant of channel form (Chapter 4). Correlation matrices have shown that narrow, stable stretches are associated with finer bed material and relatively high levels of riparian vegetation. Wider, unstable channels are associated with larger bed calibre and relatively less riparian vegetation.

Increased loading has implications for channel planform changes. Results (Chapter 4) have indicated that channel straightening and steepening has occurred in the Bell river. Predicted threshold slopes for braiding have indicated that most reaches in the Bell river are close to or above the threshold slope for braiding. Riparian vegetation, however, serves to increase bank stability, hence steeper threshold slopes are required for braiding in channels with high vegetation density. Vegetation therefore plays an important role in channel pattern stability, especially in stabilizing meanders at low flows. It may, however, increase the potential for meander cutoffs occurring on the grassy or cultivated floodplains at flows greater than bankfull.

Recent major incidences of channel instability have been identified in the transitional zone between the upper, coarser study reach (Sites 1-7) with larger clast sizes and range and the lower, finer channel reaches (Sites 8-17) with finer material and narrower ranges. As has been previously mentioned, this area is likely to be the most unstable area since it is the transition zone between the upstream bed rock channel and the downstream sediment sink zone (Warner, 1987). Pickup (1986) has stated that a transitional zone is seldom in equilibrium and therefore has a greater potential for instability.

7.2.2 TEMPORAL CONTROLS ON CHANNEL FORM

Chapter 5 has shown that there is no evidence to suggest a change in the rainfall pattern in the Bell river catchment in the last 90 years. However due to the seasonality and cyclical nature of the rainfall, flood events following years of below average rainfall may cross the threshold limit for channel stability. Daily data analysis demonstrated that wet and dry cycles are the result of an increase in the frequency of daily events rather than an increase in the magnitude of events. The coincidence of peak flows and channel straightening has been noted for cutoffs that have occurred in 1974 and 1988.

Chapter 6 indicated that changes in land-use and management practices since the early 1900s may have led to significant erosion, especially in the form of gully erosion and incised channels. This has led to a significant input of sediment into the Bell river over the last 90 years. The theoretical review has shown that changing land-use significantly effects the hydrological response of a catchment, and hence, erosion.

7.3 FACTORS CAUSING CHANNEL CHANGE IN THE BELL RIVER

According to conventional theory, channel straightening and steepening may be a response to channel aggradation through increased sediment loading (Knighton, 1987). A channel will adjust its form and pattern to transport it's load as efficiently as possible (Morisawa, 1985) (channel adjustment to disequilibrium).

Chapter 5 has indicated that major channel straightening between 1969 and 1988 was often coincidental with major rainfall and flood events. Flood events often occurred after a sustained period of below average rainfall (Drought Dominated Regimes (DDR) (Warner, 1987)). It was suggested that high rainfall and flow events may have been responsible for the exceedence of thresholds of channel stability.

Channel aggradation attenuates flood peaks (Schumm *et al*, 1984). If an altered sediment regime existed, resulting in channel aggradation, moderate to small floods may well exceed stability threshold limits, initiating channel change (this evidence would further support the critique of simple threshold between meandering and braiding channels). Large floods may have been the direct cause of channel change, however antecedent catchment and channel conditions, especially sediment load, may have established their long term geomorphic significance.

Sediment load downstream may increase continuously, or move as a series of pulses causing local channel instability. Distinction between the two is difficult. Increased load moving continuously downstream would be unlikely as the nature of the rainfall regime is such that large calibre bed material movement (from field observations) occurs only during, and immediately after, rainfall. Base flow conditions appear to produce little, if any, large calibre bed material movement. However, grain sizes of sand and below do move under baseflow conditions. This is also true for the sediment movement in the gully systems with the entrainment, movement and subsequent injection of sediment to the main channel occurring only during and after high to medium magnitude rainfall events.

The entrainment and transportation of large amounts of bed material appears to occur only during periods of bankfull or near bankfull discharge. The literature for rivers in semi-arid and mountainous catchments concurs with this (Baker, 1977; McEwan, 1989). Given the seasonality of the climate and the mountainous terrain it is likely that sediment movement within the channel occurs as a series of pulses, during periods of medium to high flow. It is this, rather than continual sediment movement downstream which creates areas of local instability. Chapter 4 has also shown how important bed material is in determining channel form. Local injections of sediment from tributaries and gulleys may be significant in determining local instability.

Increased sediment injection to the channel, together with the effect of riparian vegetation, may be the cause of channel instability in the Bell river. The planting of riparian vegetation in an attempt to stabilize the river channel may induce temporary channel stability, but may result in long term channel instability. It is hypothesized that channel instability since the turn of the century may have been a response to a changing energy input (increased sediment loads) and was therefore the natural response of the river to disequilibrium. Through the introduction of riparian vegetation, temporary bank stability was attained, but the problem of increased sediment load persisted. In order to move the increased load through the system, meander cutoffs, channel straightening and steepening occurred. This would suggest that at one level riparian vegetation may be considered to be a temporary control variable along with discharge and sediment, since temporal changes in riparian vegetation can affect channel spatial controls.

The incidence of instability may be related to its location in the long profile. The transitional area where instability has occurred is therefore that area with the greatest potential for instability to occur and is therefore extremely sensitive to fluctuating energy conditions.

Channel instability in the Bell river can be related to magnitude and frequency concepts as well the concepts of response and relaxation times. Large scale adjustments in channel pattern and form in the Bell river are achieved primarily through high magnitude, low frequency events. These events mobilize large quantities of sediment and often cross the threshold for landform stability. More frequent, low magnitude events, simply do not have the energy to induce major channel instability. High frequency events are not responsible for maintaining channel form as is found in humid regions (Pickup and Warner, 1976), but may provide the antecedent channel conditions necessary for long-term channel adjustment. As Chapter 4 has demonstrated, discharge cannot be considered to be the major independent control on channel form, especially at the local level, where factors such as sediment size and perimeter conditions are more important. Renning-Roswell and Townshend (in Petts 1985) have also shown that local gradient is related to sediment characteristics whereas channel slopes are correlated to drainage area.

Kochel (1988) has noted that channels in variable rainfall and semi-arid regions are adjusted to large floods primarily because these flows are often the only flows capable of altering channel morphology and pattern. Thresholds often exceeded in large floods are not passed by low magnitude events (Harvey, 1969; Baker, 1977; Church, 1980; Pizzuto, 1986; Carling, 1988a; McEwan, 1989).

It is suggested that low frequency, high magnitude events have an even greater impact in denuded catchments, in that they mobilize large quantities of material from the slopes, producing material for the channel, promoting further disequilibrium. Channel instability will persist and possibly increase as long as accelerated erosion increases sediment production to the channel.

Major channel adjustments in the Bell river in the past 20 years could be related to a delayed response time. Although an energy change (discharge and sediment) may have occurred since the introduction of large scale farming in the catchment, the morphological change may have been delayed (see Figure 2.1). Similarly, if landscape stability is attained in the catchment, it may be that channel instability will persist for some time.

7.4 CONCLUSION

It is concluded that channel changes in the Bell river may well be a response to human interference in catchment and channel processes. Increased sediment loading through accelerated catchment erosion would have caused channel aggradation and subsequent instability. This could have led to further channel straightening, steepening and avulsion through reducing cross-sectional area, increasing the potential for flooding. Areas of local instability are often a response to local reach controls rather than discharge conditions. The importance of catchment condition in determining channel form, bed material characteristics and pattern is also emphasized. Table 7.1 attempts to provide a model that relates channel instability in the Bell river to catchment conditions.

Table 7.1: Hypothetical Model Demonstrating the Relationship Between Catchment Condition and Channel Characteristics, Bell River

APPROXIMATE DATE	CATCHMENT CONDITION	CHANNEL FORM	CHANNEL BED MATERIAL	CHANNEL PATTERN	
Pre 1890	Stable Ecosystem, well vegetated catchment, geologically normal rates of erosion.	Stable Equilibrium Channel	Depends on Location in the long profile	Meandering channels	Braiding channels
1891-1930	Introduction of livestock to the catchment. Continuous grazing. Initiation of accelerated erosion.	Relative channel stability, increased sediment production may lead to increases in channel width and form. Depth may decline	Gradual increase in load and calibre	Meandering with local instability	Braiding with channel widening
1931-1960	Overgrazing in catchment leads to accelerated erosion and increases in runoff from the slopes.	Severe channel instability. Width and form ratio increases. Possible channel avulsion with attendant straightening and steepening.	Increased load and calibre	Braiding with possible avulsion	Braiding with channel widening
1961-1990	Introduction of rotational grazing schemes, scientific veld management and reduced stocking. Reduced slope runoff but accelerated erosion still a problem	Channel instability persists, increased form ratios and widths. Low magnitude high frequency events may periodically move temporary channel material storage downstream causing local channel instability	Load and calibre remain constant until increased load is moved through the system	Braiding with local instability	Braiding with channel widening
1991 - ? ? ?	Continual appropriate land-use and management. Reduction in sediment and runoff from the catchment	Channel instability persists, however, channel equilibrium may be attained, time period cannot be predicted. Channel width may decline accompanied by depth increase, reduced channel gradient and increased sinuosity	Depends on location in the long profile	Braiding with possible development of meander bends	Braiding but channel narrowing

CHAPTER 8

CONCLUSION

8.1 INTRODUCTION

The expressed aim of this study was to determine the causes of channel change in the Bell river. In this chapter, the major findings of the research will be discussed and related back to the study aims and objectives. Research problems as well as contribution to the subject and recommendations for further research will also be highlighted.

8.2 SUMMARY OF MAJOR RESEARCH FINDINGS

Channel changes have occurred in the Bell river in the form of meander cutoffs, channel straightening and steepening. Recent meander cutoffs occurred in 1974 and 1988. Two major groups of factors affecting the potential for channel change were identified: spatial control variables (channel factors) and temporal control variables (catchment factors). The primary spatial control variables affecting channel form and pattern have been identified as being bed material calibre and riparian vegetation.

Wider, shallower, more unstable reaches are associated with coarser bed material and relatively less riparian vegetation. Narrower, more stable sections are associated with finer bed material and relatively denser riparian vegetation. Due to the fact that few systematic progressive downstream changes in channel form variables were identified, local conditions were considered to be more important in determining channel form than longitudinal variations in discharge (traditional hydraulic geometry theory).

Evidence from Chapter 5 has shown that there has been no long term progressive rainfall trend, in either the annual or the seasonal data for the period of meteorological record. An important characteristic of the rainfall is the existence of distinct wet and dry cycles with peaks every 16 to 19 years. Evidence from the daily data demonstrated that wet and dry cycles are the result of an increase in the frequency of rainfall events rather than an increase in the magnitude of events. It is thus rainfall cycles and fluctuations, and the nature of a major flood in relation to the relatively wet periods during which vegetation is reestablished, rather than progressive trends which are important determinants of channel and catchment hydraulic and sedimentological processes.

The incidences of channel major instability since 1952 have been located in the transitional zone between the upper, coarse reaches and the lower, finer reaches. Distinct channel form and bed material differences are apparent in these two zones. This transitional zone is similar to those described by Pickup (1986) and Warner (1987).

A significant increase in sediment input to the Bell river has occurred in the last 90 years. Results from the sequential erosion mapping have indicated that erosion has increased significantly in the catchment, especially in the form gulleys and incised channels. There is evidence to suggest that this could have been in response to catchment and land-use management change, especially overstocking since the introduction of full scale stock farming after the 1890s. The injection of large volumes of material into the catchment has inevitably had important impacts on the channel.

It was concluded that channel changes in the Bell river are possibly a response to anthropogenic influence in both catchment and channel processes. Increased sediment loading to the channel would have caused channel aggradation and attendant instability. The planting of riparian vegetation, in response to channel instability (thereby treating essentially the effect and not the cause), lead to perimeter stability in the short term at flows less than bankfull discharge, but served to reduce cross-sectional area, thereby increasing the potential for flooding and meander cutoffs.

Although flood peaks in 1974 and 1988 exceeded channel stability thresholds, initiating observed channel change, antecedent channel form and condition may have ensured their long term geomorphic significance. Modern channel instability in the Bell river channel could be directly related to man's influence on catchment and channel processes. Channel instability in the Bell river will persist as long as there is a continual supply of sediment to the channel. The downstream movement of bed material, as a series of sediment pulses, could be expected to continue to create areas of local instability in the channel and may lead to further channel straightening and steepening. Channel change in the Bell river is essentially a response of the river to disequilibrium. To substantiate this requires continued monitoring of channel conditions.

8.3 RESEARCH PROBLEMS

Perhaps the major problem encountered with this research was the lack of available data. The lack of flow data proved to be a problem as discharge is one of the most important variables affecting channel form and pattern. The use of estimated bankfull discharge, based on drainage area, is not ideal. As no alternative was available, however, this was used together with regional flow data. Problems in correctly measuring Manning's n, channel and bank material and channel gradient were also encountered, but these are universal problems in this field of research.

The problem of bed material sampling was especially difficult, in that an attempt was made to reliably represent channel bed material for a 17 kilometre reach of the river. This was especially so as the sampling occurs at one moment in time, at a particular flow level (usually as low as possible) and may therefore seriously bias results. The lack of adequate means to quantify the effects of riparian vegetation was also a problem, as this inevitably lends itself to a degree of subjectivity.

Similar data problems were associated with rainfall and catchment land-use and management data. Without adequate evidence, defining a causal link between land-use management and accelerated erosion was a problem. Rainfall data from the top of the catchment would have been ideal, as this is the main runoff producing area, with higher rainfall received.

The use of proxy data for determining historical rainfall, catchment land-use and management strategies, and flood trends were considered, as have been used by other authors (Nicholson, 1981, 1986; Herlihy, 1980). South Africa, however, lacks written historical sources and no documents or maps to this effect could be located. The lack of adequate stock figures for the catchment necessitated the use of regional figures. The census reports stated that stock numbers given in the census probably underestimated stock numbers, as farmers feared higher taxes if they indicated true stock numbers. This was considered by the author to provide further evidence of regional overstocking.

Another problem encountered was the scale of research. Attempting to consider catchment and channel processes for a 424 kilometre square mountainous catchment proved a formidable task, especially due to lack of data. The advantage of taking a catchment scale view is that this enables a more holistic approach to the problem. The problem of identifying cause and effect relationships was especially problematic. It has been shown that channel instability has occurred coincidentally with, and following, accelerated erosion in the catchment, but there is no definitive evidence to draw cause and effect relationships. Many of the conclusions therefore remain essentially speculative rather than established fact. Due to the nature of the research, many different variables needed to be considered when determining the causes of channel change. The structure of the thesis reflected this. Thus, Chapters 4, 5 and 6 are essentially research topics in their own right. This made the linking of these chapters difficult. Attempts to integrate the information in the chapters to determine the causes of channel change proved complex.

8.4 CONTRIBUTION TO SUBJECT AND RECOMMENDATIONS FOR FUTURE RESEARCH

As previously mentioned, work on South African fluvial systems is limited. It is hoped that this research will contribute to the knowledge and understanding of South African fluvial systems. Furthermore, this research has emphasized the importance of the interdependence of catchment and channel processes. The importance of human impact on the fluvial system has also been identified. This is important as ecologists and land managers often fail to understand the symbiotic relationship between catchment and channel condition.

This work has stressed the importance of riparian vegetation in determining channel form and pattern. Traditional theory pays scant attention to the importance of considering riparian vegetation as a major variable determining channel form and pattern, both as a spatial and a temporal control variable. It is only recently that the importance of riparian vegetation acting both as a spatial and temporal control is being recognized (Thorne and Osman, 1988, Thorne, 1990). Perhaps these could be considered in hydraulic geometry equations.

The impact of low frequency, high magnitude events in regions with a seasonal rainfall pattern are probably more important in determining channel form than high frequency, low magnitude events. This is especially so in semi-arid and mountainous areas. The use of hydraulic geometry equations tended to show the inappropriateness of their applicability to semi-arid and seasonal rainfall regions. This is emphasized in channels that are in disequilibrium, where local channels are in adjustment to factors other than bankfull discharge, especially local reach conditions. It is these conditions that determine the long-term geomorphic effectiveness of floods. The use of hydraulic geometry equations to predict channel form, pattern, bed-load and calibre, especially in unstable streams, would appear to be inappropriate, as they represent the equilibrium relationship.

In recommending directions for future research the following might be considered. Long term monitoring of sediment movement within the channel and the gulleys systems in an attempt to relate this to areas of local instability. This can be achieved through sequential monitoring of fixed point surveys along the channel, for both bed material volume and calibre. This would enable the monitoring of rates of movement of bed material, and may aid in the determination of sediment pulses moving through the system. Channel form response to changing load and calibre could then be identified.

The possible use of traces could also be considered. This applies not only to channel bed movement, but also material movement off the slopes. This would help identify the relationship between sediment source and sink areas, as well as the magnitude and frequency of movement of different material sizes. To determine volume movements off the slopes and through the channels, some form of bedload trap method could be used. This could be related to the magnitude and frequency of flow events. These would be relatively inexpensive methods to adopt and could be handled by a well trained research team.

A method to reliably quantify the effect of riparian vegetation on bank stability would help considerably in assessing channel form and pattern. A shear strength test may work, but it would have to take account of the relative effectiveness of different soil properties. The simple silt-clay percentage may be useful in large river systems, but is not appropriate for small scale studies.

The identification of palaeochannels and systems could be undertaken through coring across the flood plain and remnant meander cutoffs. Geophysical techniques might also be applied. This would enable the identification of ancient channel movements and possibly past climatic conditions. An understanding of the palaeohydrological conditions may aid the understanding of present day problems of channel instability. This however would be an expensive undertaking and require specialist knowledge and equipment.

The use of paired catchment studies may be useful. If it were possible to find a suitable 'pristine' catchment, with similar geology, size and so on, it may be possible to draw a causal link between channel form and pattern and catchment condition. The problem of obtaining a suitable catchments is the main limiting factor.

Given the resource constraints, lack of available data and length of time allowed for the completion of the study, it was felt that the most appropriate research design was adopted. Process studies are always difficult due to the unpredictability of occurrence of significant events. Monitoring of the channel, catchment and fixed point cross-sections will continue. Given the cyclical nature of the rainfall it is hoped that the present drought may soon be broken then, perhaps, further channel instability will occur which can be studied.

8.5 CONCLUSION

In conclusion, an assessment will be made of the success in achieving the original aims, these were stated as:

1) To determine river channel changes in the Bell river in terms of channel form and pattern in the last 40 years.

2) To assess the possible causes of channel instability. These may include altered hydraulic and sediment regime due to catchment land-use and management, climatic change or intrinsic thresholds that may have been exceeded.

Channel change has occurred in the Bell river in terms of meander cutoffs, general channel widening, straightening, steepening and reduction in sinuosity. Recent incidences of major instability have occurred in the transition zone between the upper, coarser bedded reaches and the lower, finer bedded reaches.

Channel instability is thought to have been related to increased sediment loads in the channel following accelerated erosion in the catchment, which was possibly caused by poor land-use and management practices in the recent past. High magnitude, low frequency events are probably the direct cause for crossing thresholds of stability, however antecedent catchment and channel conditions (sediment load, calibre and riparian vegetation conditions) may have ensured their long term significance. Channel instability in the Bell river is primarily a response to disequilibrium.

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APPENDIX A

CHANNEL TRANSECT SURVEYS

April 1990		October 1990		April 1991		November 1991	
TRANSECT NUMBERS (SEE FIGURE 1.3) FIGURES IN METRES							
A-B		A-B		B-A		A-B	
Height	Distance	Height	Distance	Height	Distance	Height	Distance
3.775	0	3.775	0	3.995	44.6	4.183	0
3.695	3.4	3.655	2	3.79	38.4	3.775	13.8
3.695	4.8	3.67	5.9	3.6	32.8	2.85	14.2
3.7	6.15	2.875	6	3.042	31.9	1.305	18
2.525	7.2	2.235	7.5	2.785	27.4	1.081	20.2
2.28	8.1	1.355	9.5	1.305	23.4	1.367	23.5
1.78	8.75	1.235	12	1.173	22.4	1.61	29.3
1.3	10.2	1.195	16	1.345	19.9	1.9	34.4
1.24	14.4	1.215	21	1.227	16.8	2.902	37.5
1.22	17.3	1.215	23	1.275	12.6	3.31	42
1.33	20	2.495	24	1.4	9.4	3.655	42.1
1.18	21.75	3.195	32	1.86	8.1	3.82	54
1.35	23.8	3.555	32.2	2.93	6.1		
1.76	25	3.715	39.5	3.68	6		
2.385	26.4	3.715	42.6	3.775	0		
2.88	29.5						
3.14	32.2						
3.59	32.5						
3.66	35						
3.8	40						
3.75	44.8						
C-D		C-D		D-C			

Height	Distance	Height	Distance	Height	Distance		
3.46	45.49	3.612	44.5	3.595	0		
3.28	40	3.167	38.5	3.375	3.9		
3.07	35	2.977	32	2.155	4.5		
2.89	30	2.677	26	1.75	5.5		
2.69	25.8	2.137	24.5	1.345	5.7		
2.37	24.9	1.595	19	1.4	9.2		
2.14	24.1	1.152	16	1.405	11.7		
1.94	22.6	1.437	12	1.36	15.7		
1.68	20.6	1.517	10	1.078	19		
1.38	19	1.577	4.5	1.687	19.8		
1.36	16.3	2.177	4	2.128	23.6		
0.98	13.4	3.372	3.8	2.82	28.3		
1.19	9.2	3.517	2	3.03	34		
1.38	6.8	3.595	0	3.32	40.5		
1.98	5.4			3.43	43.7		
2.15	4.8			3.44	45.1		
2.775	4.6						
2.87	4.25						
3.33	4.2						
3.545	2						
3.595	0						
H-I		H-I		H-I		H-I	
Height	Distance	Height	Distance	Height	Distance	Height	Distance
3.505	0	2.242	16	3.505	0	2.37	15.3
2.985	2	1.89	14.5	2.813	2.7	1.99	13.9
2.435	4.4	2.11	11	2.23	6	2.063	12.7

2.14	6.6	2.122	6	2.13	9.8	1.935	10.1
2.065	7.9	2.725	3.2	1.85	14	2.45	4.7
2.125	9.9	3.29	1.5	2.33	15	3.227	1.3
2.075	11.7	3.505	0			3.505	0
2.055	12.9						
1.815	13.9						
2.005	14.9						
2.245	15.1						
C-G		C-G		G-C		G-C	

Height	Distance	Height	Distance	Height	Distance	Height	Distance
3.44	0	3.44	0	2.4	26	3.44	0
3.42	3.5	3.405	4	1.98	25.1	2.922	15
3.165	10	3.18	10	2.205	22.3	1.928	18.6
2.845	16	2.905	16	2.02	18.7	1.836	19.8
2.455	17	2.015	18	2.07	17.9	2.113	21.1
2.115	18	2.105	24	2.835	15.8	1.5	24.1
1.98	19	2.32	28	3.17	10.1	1.783	25.3
2.125	20			3.44	0	2.398	25.5
2.155	22						
2.085	23						
1.885	25						
2.19	26						
C-F		F-C		F-C		C-F	

Height	Distance	Height	Distance	Height	Distance	Height	Distance
3.46	0	3.205	52.5	3.46	0	3.726	50.1
2.965	2	1.2	48	2.842	3.3	3.455	31.5
2.66	7.8	0.925	44	2.635	7.6	3.15	28.4
2.465	8.2	0.585	38	2.435	12	2.87	19.7
2.315	9	1	32	2.635	14.3	2.464	12.1
2.375	12	1.22	24	2.93	19.5	2.22	10.5
2.48	13	1.625	20	3.1	27.1	2.835	7.9
2.755	18	1.605	14	3.515	30.4	2.867	3.3
2.995	22	3.365	5.5	3.445	37.3	3.46	0
3.06	27	3.46	0	3.615	43.3		
3.18	29.3			3.775	50		
3.47	30						
3.385	35						
3.53	41						
3.685	45.5						
3.75	48.5						
3.775	50						
B-E		E-B		E-B		B-E	
Height	Distance	Height	Distance	Height	Distance	Height	Distance
3.55	0	2.81	24	2.795	22.9	3.55	0
3.5275	2.75	1.85	22	2.01	22.1	3.585	7.9
3.41	6	1.785	17.5	1.985	19.5	2.582	8.9
3.505	8	1.47	15	1.665	15.1	2.095	11.9
2.42	9	1.388	14	1.665	12.9	1.472	13.2
2.245	11	2.525	8.5	2.585	8.7	1.596	14.2
1.74	12	3.49	8.3	3.485	8.2	1.867	18.2

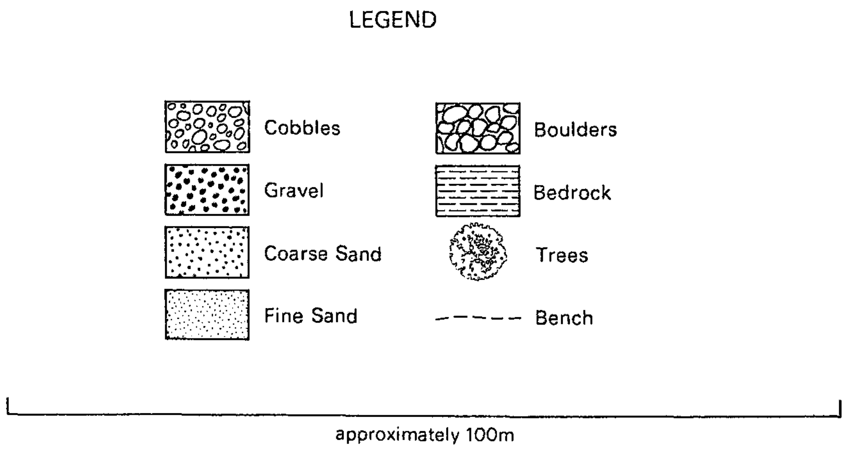
1.37	14	3.345	6	3.55	0	1.955	20.4
1.595	15	3.55	4			2.055	21.7
1.725	17	3.55	0			2.84	23.7
1.925	19						
1.785	21						
2.195	22						
2.825	24						
J-K		K-J		K-J		J-K	
Height	Distance	Height	Distance	Height	Distance	Height	Distance
4.355	0	4.64	73.2	4.37	78.6	4.73	0
4.38	21	4.665	72.5	4.38	69.7	4.67	20.7
4.3	21.2	4.585	70	3.43	69.4	3.948	20.8
3.675	23.5	3.96	70	2.9	67.7	3.078	24.1
2.72	26.3	3.005	68	1.62	67	2.135	29
1.56	27.3	1.845	66	1.54	62.2	2.78	36.2
1.535	29.3	1.82	64	1.565	58.8	2.86	41.9
1.575	31.3	1.86	60	1.76	53.8	2.62	49.7
1.68	38.5	1.965	59	2.59	53.3	1.538	49.8
1.8	44.3	2.085	54	3.13	45.6	0.765	54.7
2.56	50.1	2.845	53	2.99	39.1	1.115	59.7
3	52.6	3.285	50	2.7	34.3	1.23	65.7
3.135	53.3	3.42	44.5	2.17	30.2	2.82	68.3
2.94	58.8	3.225	40	2.67	26.6	3.79	69
2.776	62.3	3.061	35.5	3.175	25.5	3.668	77.5
2.49	65.3	2.775	33.5	3.42	23.2		
2.158	66.3	2.443	31	3.85	22.1		

2.56	66.8	2.845	28	4.67	21.6		
3.16	68.9	3.445	26	4.64	0		
3.32	72.5	3.605	24				
4.64		4.925	22.5				
4.595		4.88	18				
4.64		4.925	0				
L-M		M-L		L-M		L-M	
Height	Distance	Height	Distance	Height	Distance	Height	Distance
4.787	63	4.775	0	5	69.8	5.037	70.9
2.977	62.6	4.655	2	4.885	63.6	4.837	66.9
2.377	61.6	4.705	8	3.245	63.2	2.402	65.4
1.537	59.6	3.085	9.5	1.935	61.4	1.617	64.7
1.492	57.6	2.778	11.5	1.475	59.8	1.517	61.9
1.877	52.6	2.835	15.5	1.745	55.9	1.867	55.4
1.827	50.9	3.08	21.5	1.995	52.3	2.197	49.9
1.947	47.7	3.34	25.5	2.005	49.4	2.477	44.8
2.437	46.6	3.3	31.5	2.515	45.4	1.857	41.2
2.127	44.6	2.876	37.5	1.875	41.6	2.037	39.7
1.707	40.1	1.735	40.5	3.115	37.4	3.332	25.3
1.867	38.6	1.8	41	3.325	25.3	2.917	19.5
3.097	37.3	2.301	45.5	3.125	22.5	2.86	13.5
3.342	25.4	2.04	47.5	2.965	17.5	3.809	8.1
3.227	22.6	2.015	49	2.79	12.4	4.757	8
2.945	19.5	1.98	51.5	3.845	7.4	4.782	2.9
2.957	17.1	1.84	53.5	4.72	6.8		
2.827	14.2	1.58	55.5	4.775	0		
2.907	11.5	1.475	57.5				
3.307	8.35	1.805	59.5				

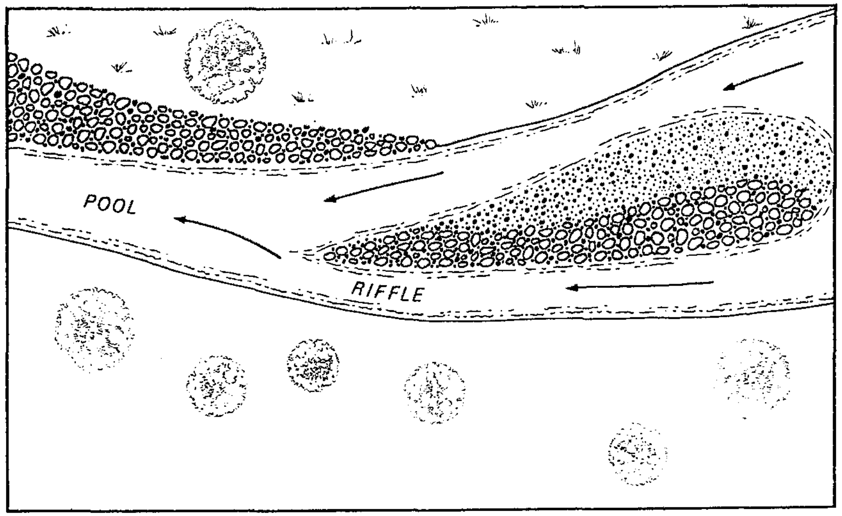
4.697	6.85	2.635	61.5				
4.775	0	3.1	62.5				
		4.84	62.9				
N-O		N-O		O-N			
Height	Distance	Height	Distance	Height	Distance		
4.595	0	4.595	0	4.885	65.8		
4.212	8.7	4.494	5.8	4.065	65.4		
3.575	8.8	4.28	9	2.995	62.1		
2.975	16.9	4.101	11	1.505	61.5		
2.945	22.5	3.435	15.6	1.855	58.6		
2.9	28	2.982	19	2.045	53		
2.965	33.4	2.9	28	2.58	44.4		
2.995	41.5	3.02	37	2.995	34.9		
2.37	48.5	2.52	44	2.89	28.2		
2.05	53.3	2.1	53	2.965	19.7		
1.785	58	2.035	54	3.125	12		
1.7	61	1.84	56.5	3.255	10.5		
3.055	62	1.92	58	4.265	8.6		
4.225	65	1.575	60	4.595	0		
4.895	66	1.54	62				
4.91	67	2.725	63				
		3.36	64				
		4.26	65				
		4.88	65.5				

APPENDIX B

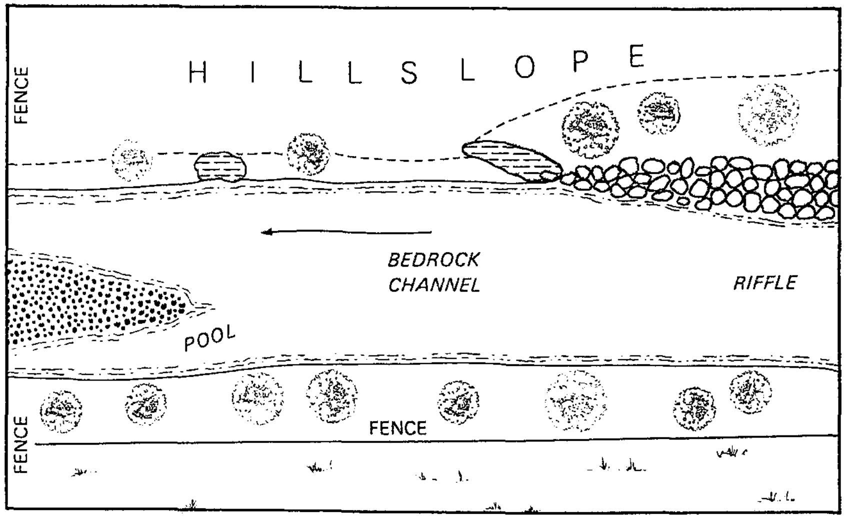
SKETCH MAPS, SURVEYED SITES



Section 1



Section 2



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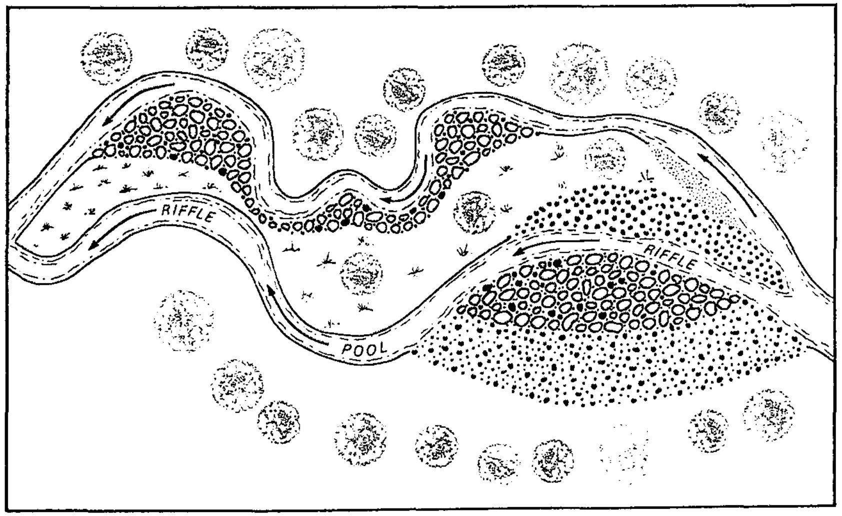

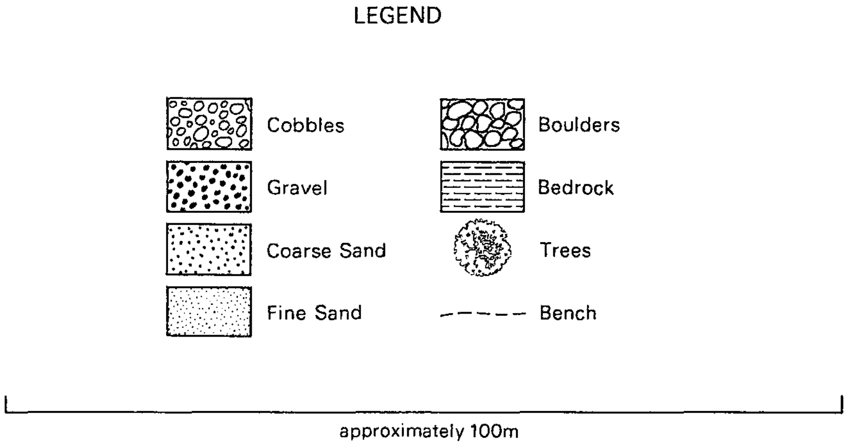

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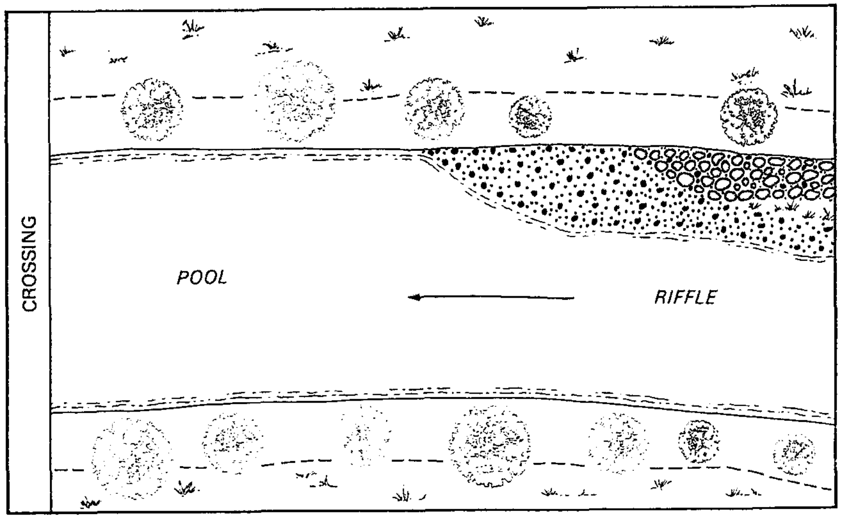

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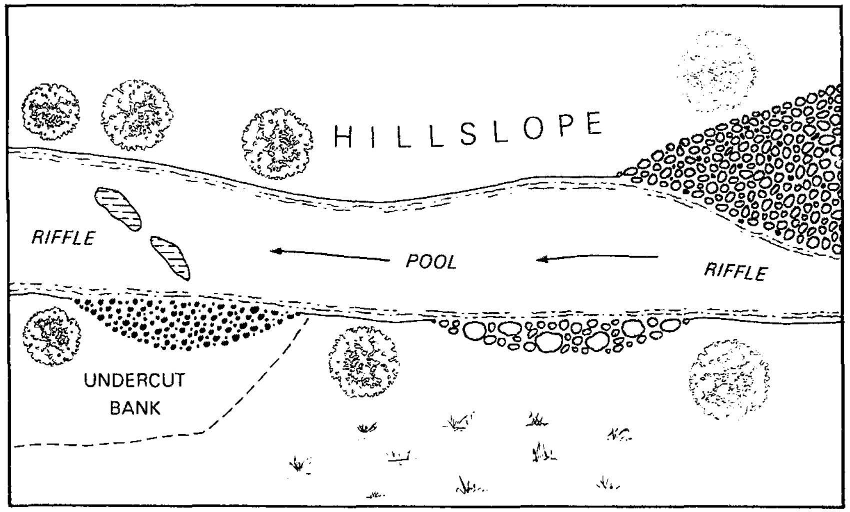

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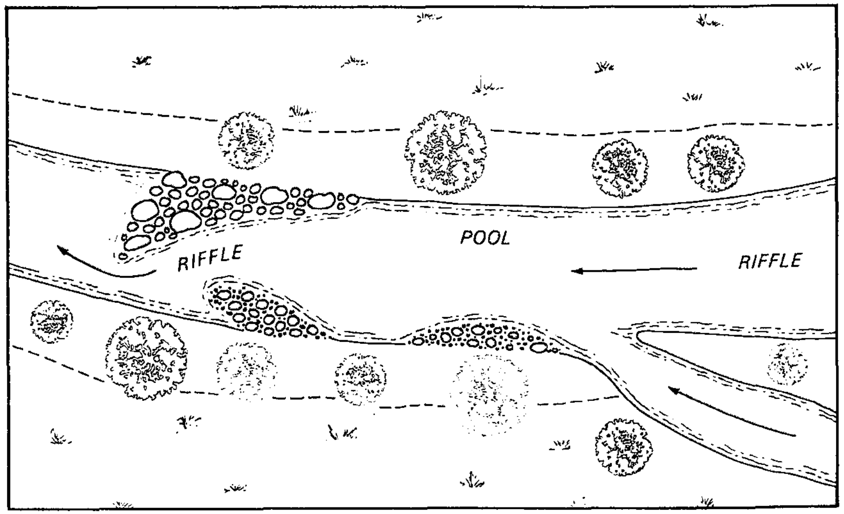

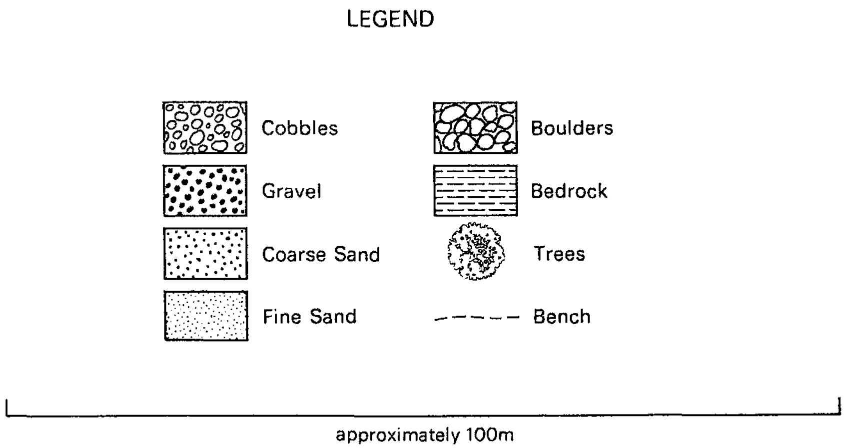

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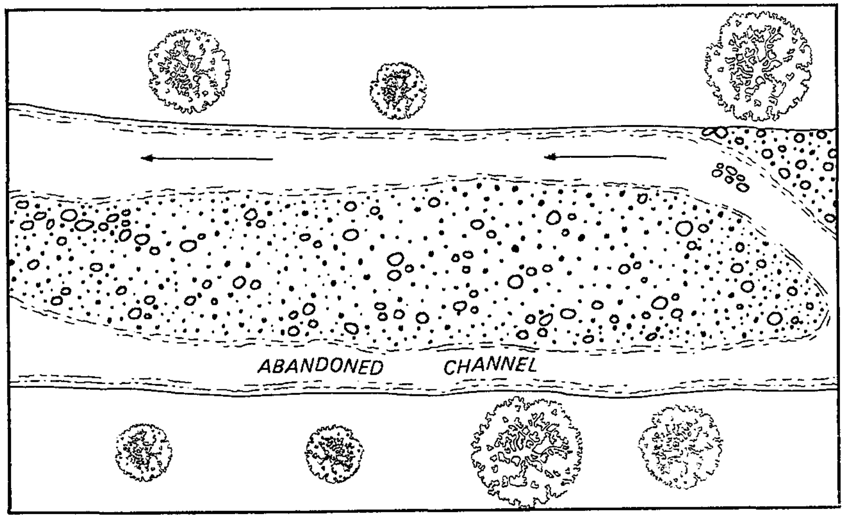

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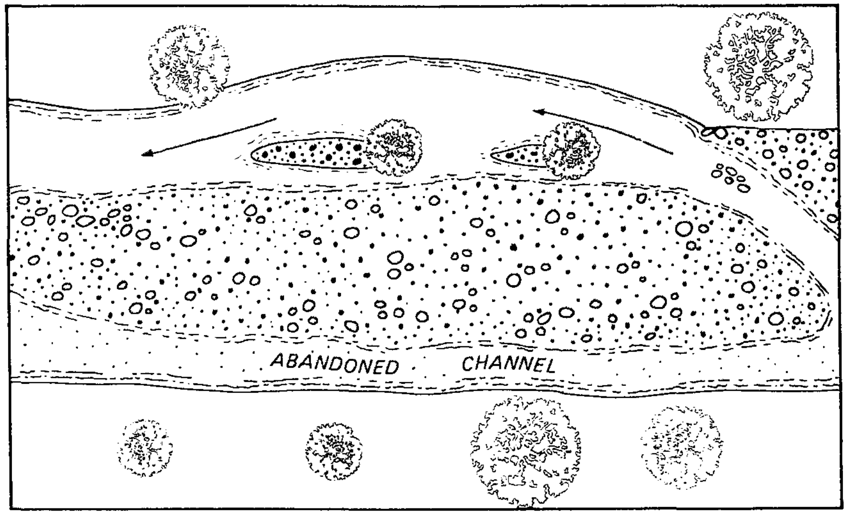

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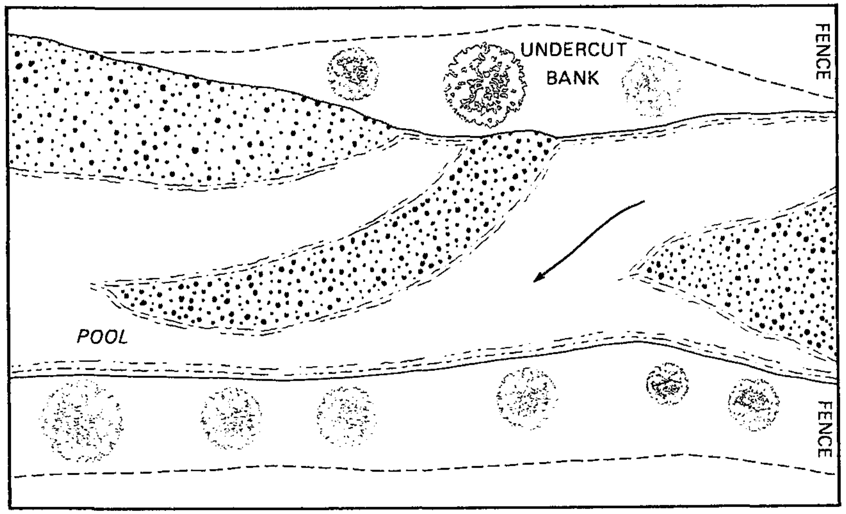

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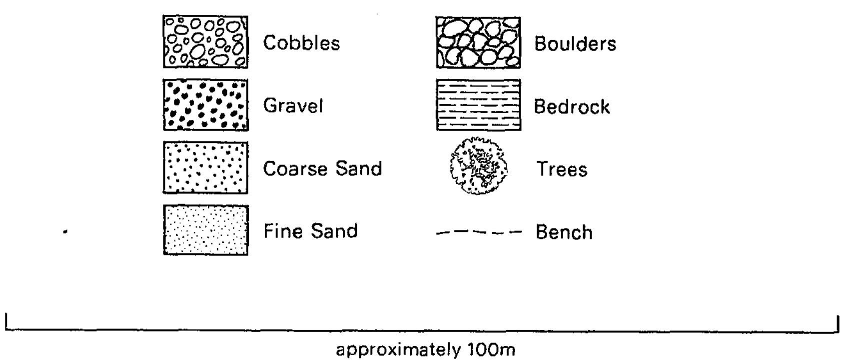

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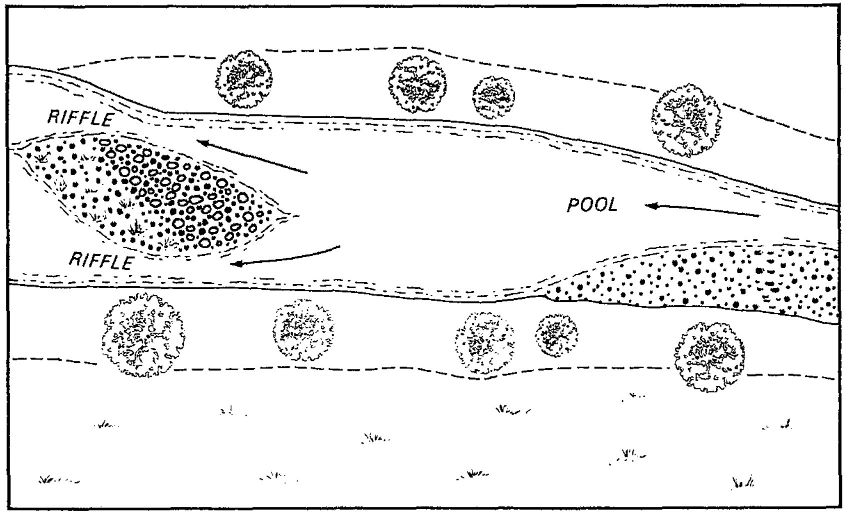

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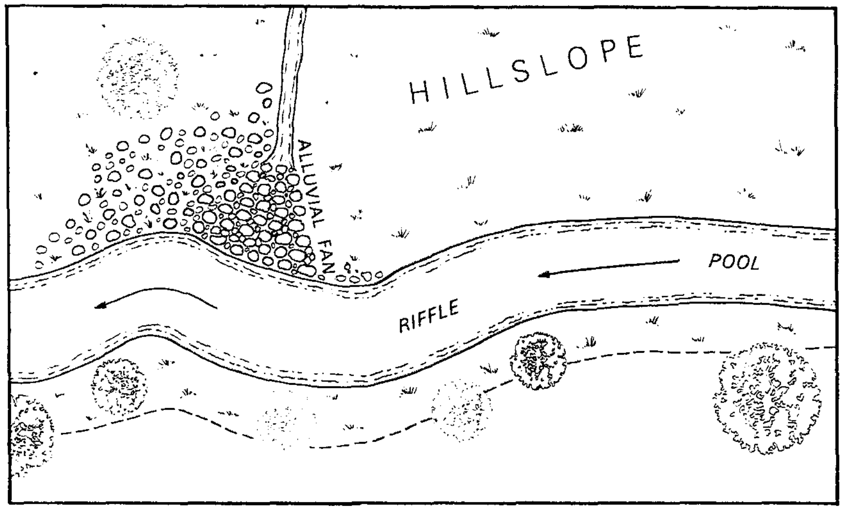

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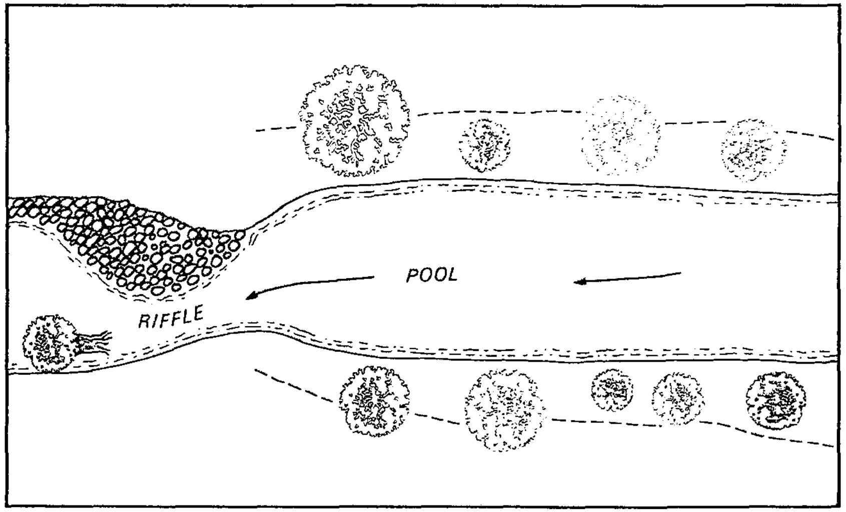

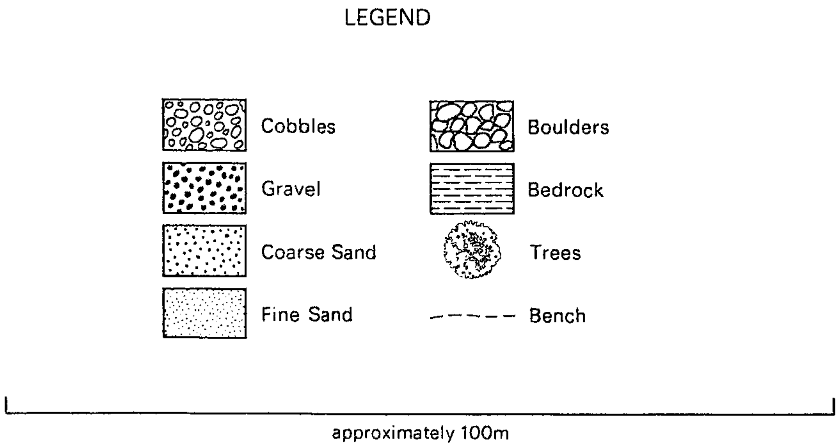

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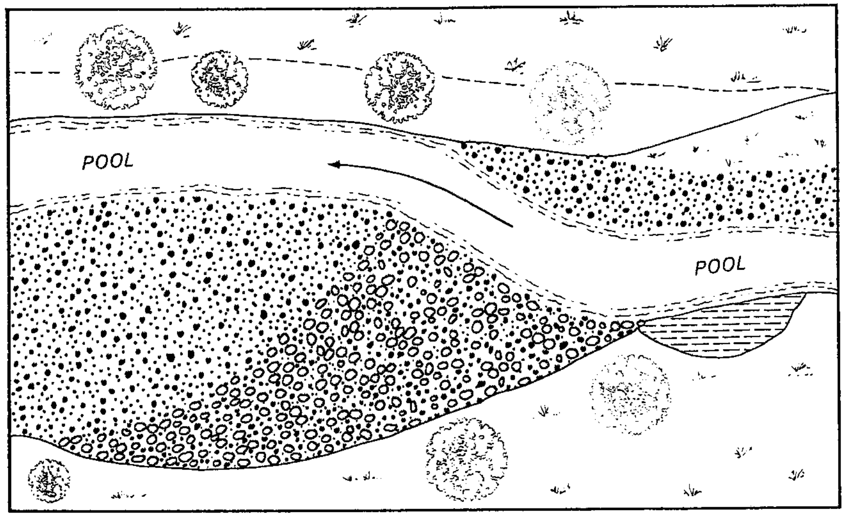

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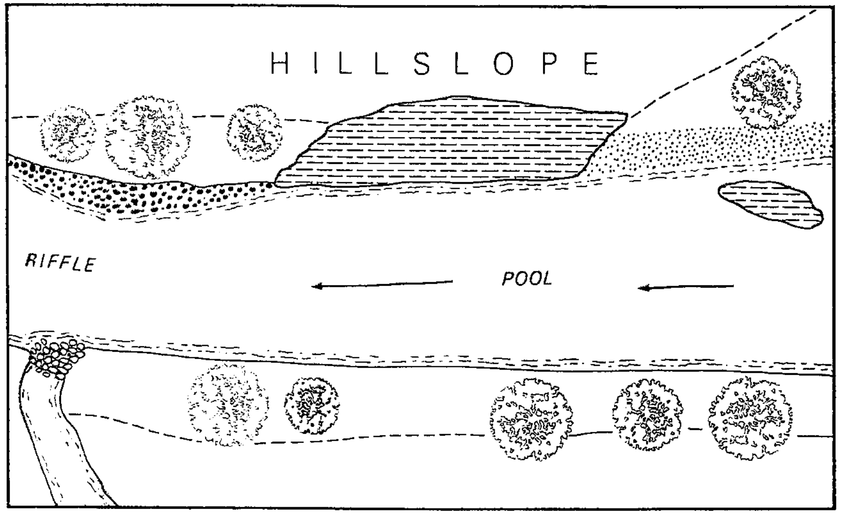

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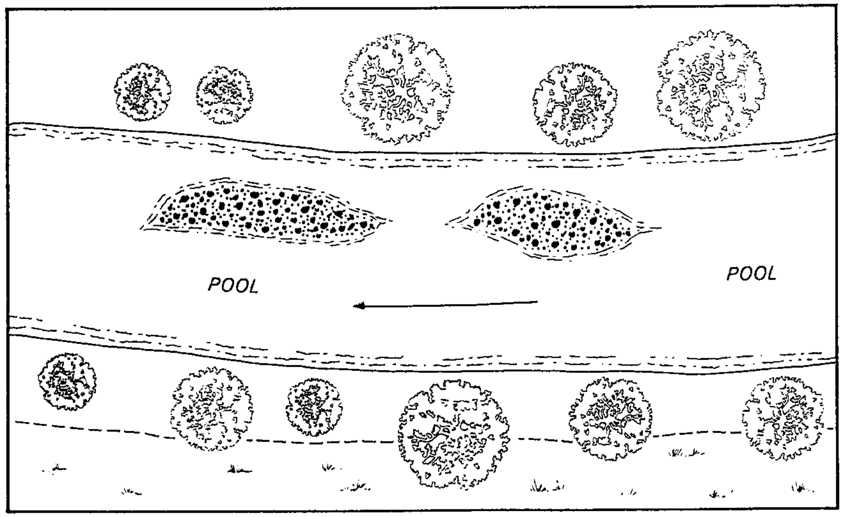

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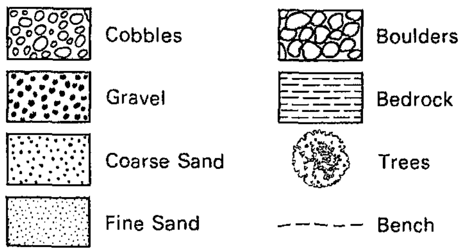
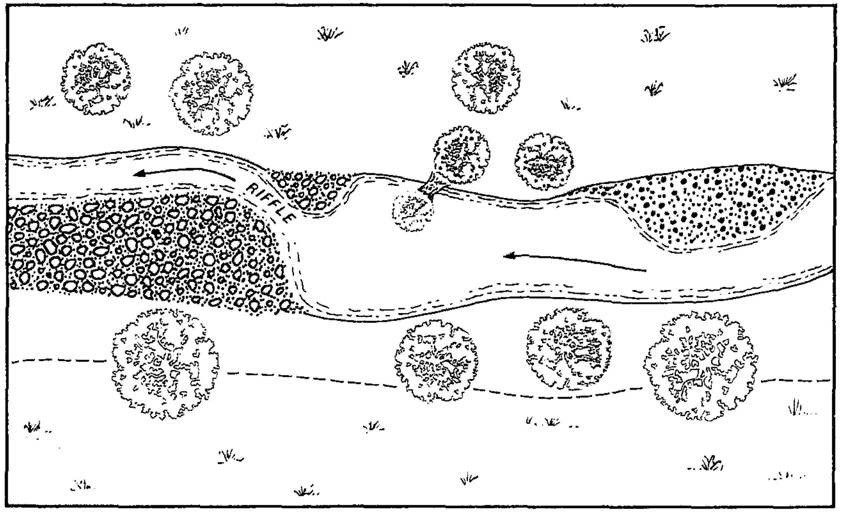
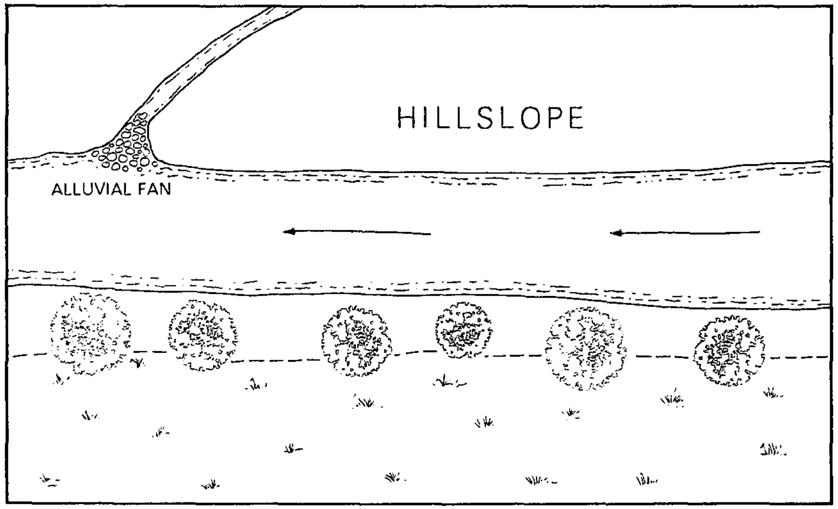


approximately 100m

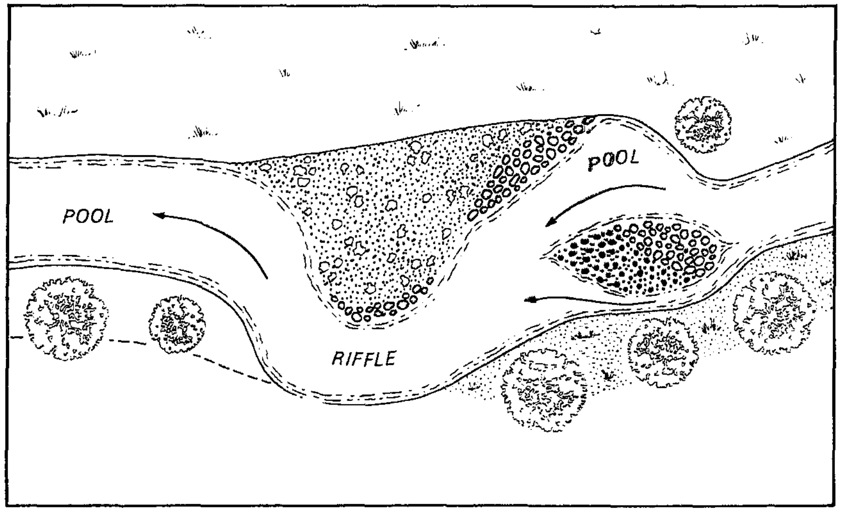
Section 15



Section 16



Section 17



APPENDIX C

SITE SURVEYS

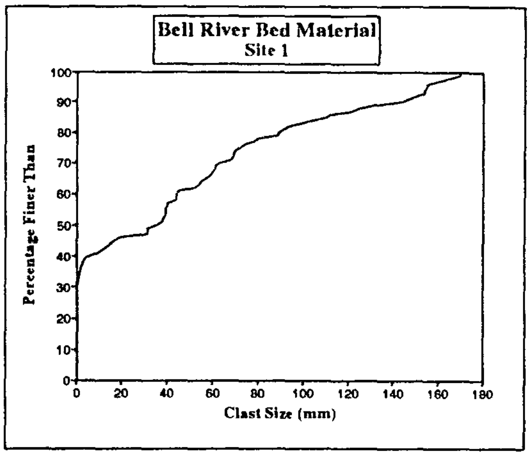
Site 1	1		2			3	
			FIGURES IN METRES				
Height	Distance		Height	Distance		Height	Distance
-1	5.5		0	0		0	68.8
-1.68	6		-0.165	1.8		-0.625	65.8
-2.128	8		-0.465	4		-0.48	61.8
-2.718	8		-0.63	7.5		-0.3	58.5
-3.058	9.5		-1.887	7.6		-1.765	57.8
-3.118	11		-2.465	9.5		-2	56.3
-3.208	13		-2.895	11		-2.45	55.5
-2.278	25		-2.875	12.8		-2.23	53.3
-1.868	40		-2.477	20.3		-1.825	52.8
-1.368	42.5		-2.015	22.5		-1.675	51.8
-1.038	44		-1.66	35		-1.81	34.8
-0.938	47		-1.07	40		-2.09	31.5
-0.868	53		-0.28	59		-1.895	29.3
-0.418	56.5		-0.475	66		-1.375	28.8
			-0.67	67.2		-1.03	24.5
			-0.65	77.5		-0.005	22.2
			-0.59	82.3		-0.408	18.6
			-0.435	104		-0.065	0
Site 4			Site 6			Site 8	
						1	
Height	Distance		Height	Distance		Height	Distance
-0.43	0		-0.118	46.5		0	44.5
-0.97	3		-0.128	42.2		-0.53	40
-1.41	6		-2.348	41.5		-1.93	37.5
-4	7		-2.488	40		-3.91	36.5
-3.925	10		-2.348	27.5		-3.53	26.5
-3.785	12.5		-1.875	25.4		-3.04	19.5
-3.915	17		-1.308	16.5		-3.5	5.5
-3.875	19		-0.145	12.1		-1.782	5
-1.285	26		0	9.5		-1.664	4.5

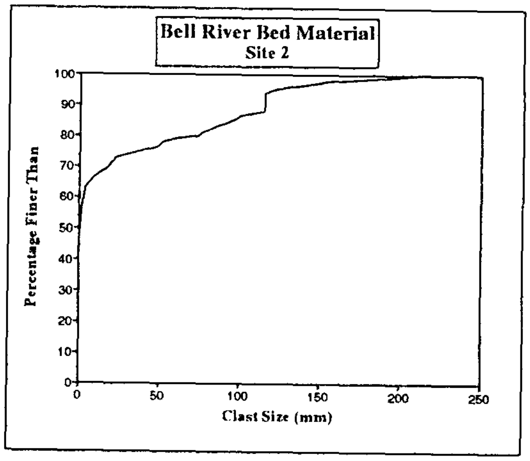
-0.97	3		-0.128	42.2		-0.53	40
-1.41	6		-2.348	41.5		-1.93	37.5
-4	7		-2.488	40		-3.91	36.5
-3.925	10		-2.348	27.5		-3.53	26.5
-3.785	12.5		-1.875	25.4		-3.04	19.5
-3.915	17		-1.308	16.5		-3.5	5.5
-3.875	19		-0.145	12.1		-1.782	5
-1.285	26		0	9.5		-1.664	4.5
-0.935	38					-1.197	4.25
						-0.787	2.75
						-0.624	0
Site 8			Site 10			Site 12	
2							
Height	Distance		Height	Distance		Height	Distance
0	31		0	41		0	30.8
-2.4	29		-0.23	28.4		-0.124	28.5
-2.29	14.5		-1.731	24.5		-2.636	24.7
-2.29	13		-2.858	23.2		-3.076	23.8
-1.39	8		-2.638	14.8		-2.886	19
-0.39	3.5		-2.172	6.3		-3.092	14.3
			-1.142	4.6		-2.804	14.2
			-0.692	3.6		-2.636	13.3
			-0.447	3		-2.321	12.3
			-0.277	0		-1.839	11.5
						-1.368	10.1
						-0.417	8.6

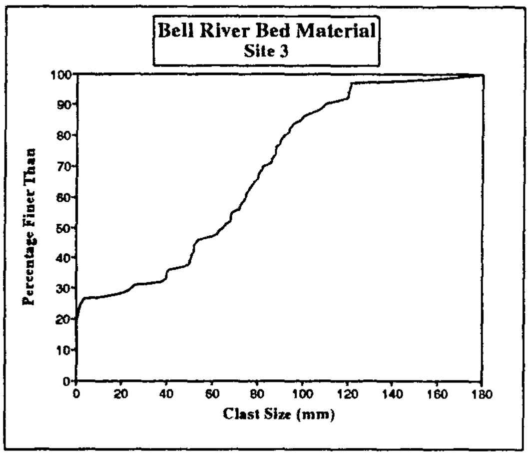
						-0.644	6.6
						-0.505	5.6
						-0.133	4.3
						-0.02	1.5
Site 14			Site 15			Site 17	
Height	Distance		Height	Distance		Height	Distance
-1.895	38		0	34.7			
-1.895	30.8		-0.242	32.5		-2	33.4
-3.032	28.4		-0.83	30.9		-1.655	29.5
-3	28.2		-1.361	29.9		-2.131	27.5
-3.982	26.6		-4.14	27.8		-2.86	19.8
-3.922	21.9		-3.625	22.9		-3.6	18.4
-4.035	16.6		-3.341	20.1		-4.27	12
-3.816	16.2		-3.052	15.6		-3.537	8.2
-3.527	14.3		-1.886	14.1		-2.728	7.1
-3.075	12.9		-0.898	11.1		-2.083	5.9
-2.186	10.7		-0.65	8.9		-1.4	1.5
-1.965	6.6		-0.45	2.7		-0.855	0
-0.698	5.3		-0.277	0			
-0.13	3.6						
-0.01	2.4						

APPENDIX D

BED MATERIAL FOR 17 SITES


Bell River Bed Material
Site 1
Percentage Finer Than
0 10 20 30 40 50 60 70 80 90 100
0 20 40 60 80 100 120 140 160 180
Clast Size (mm)


Bell River Bed Material
Site 2
Percentage Finer Than
0 10 20 30 40 50 60 70 80 90 100
0 50 100 150 200 250
Clast Size (mm)


Bell River Bed Material
Site 3
Percentage Finer Than
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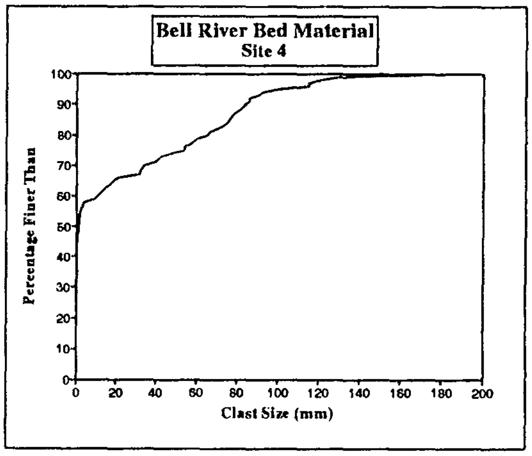
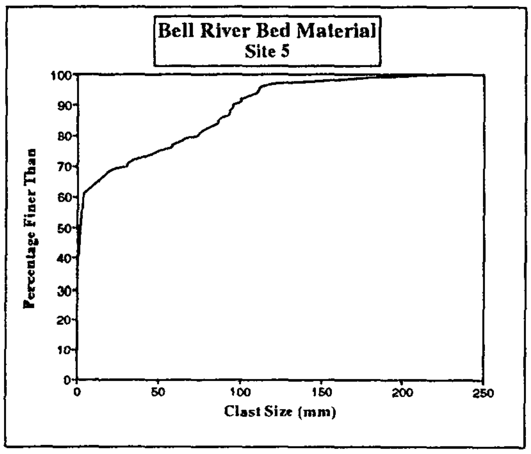
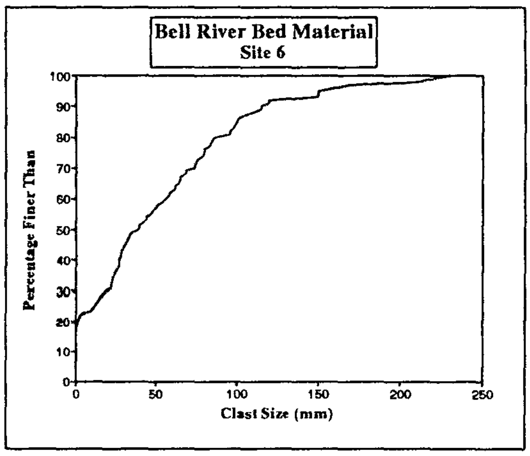
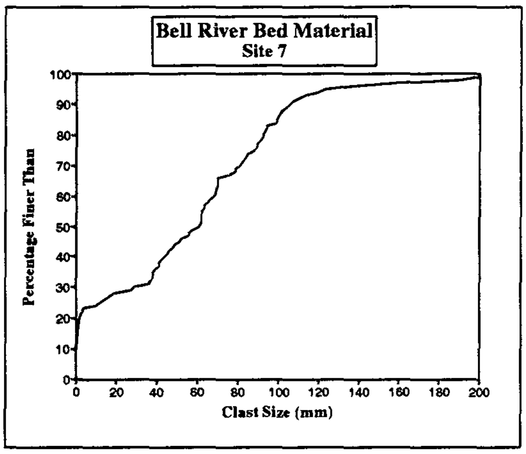
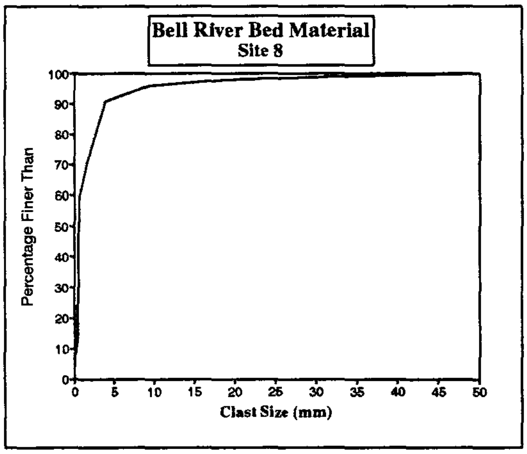
0 20 40 60 80 100 120 140 160 180
Clast Size (mm)

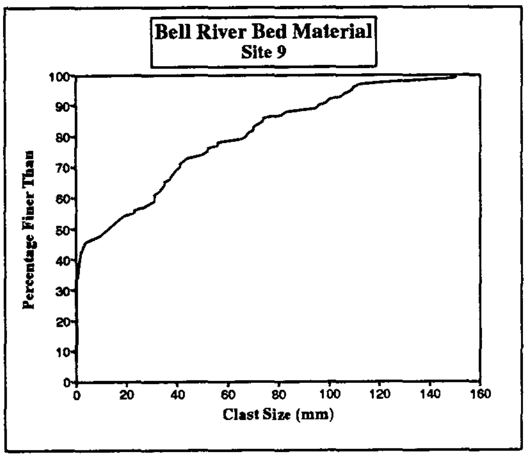

Bell River Bed Material
Site 4
Percentage Finer Than
0 10 20 30 40 50 60 70 80 90 100
0 20 40 60 80 100 120 140 160 180 200
Clast Size (mm)

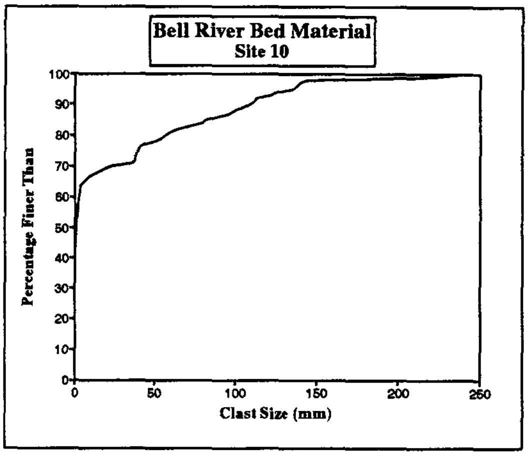

Bell River Bed Material
Site 5
Percentage Finer Than
0 10 20 30 40 50 60 70 80 90 100
0 50 100 150 200 250
Clast Size (mm)

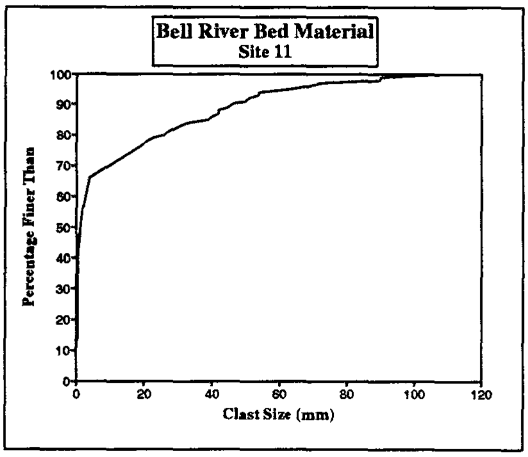

Bell River Bed Material
Site 6
Percentage Finer Than
0 10 20 30 40 50 60 70 80 90 100
0 50 100 150 200 250
Clast Size (mm)

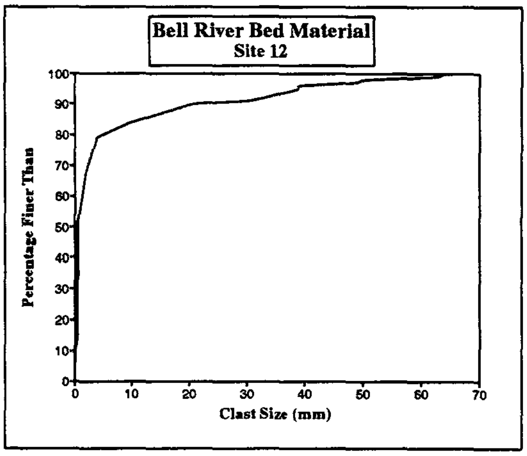

Bell River Bed Material
Site 7
Percentage Finer Than
Clast Size (mm)
0
10
20
30
40
50
60
70
80
90
100
0
20
40
60
80
100
120
140
160
180
200

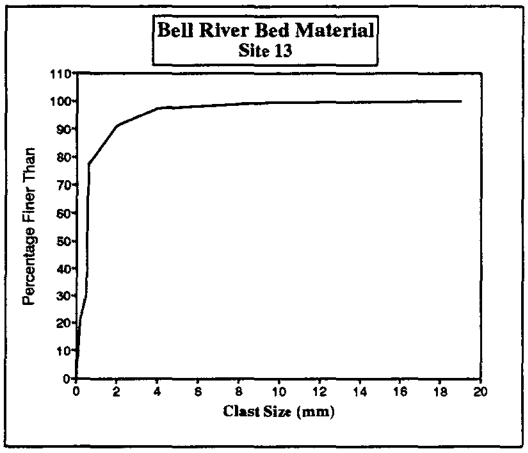

Bell River Bed Material
Site 8
Percentage Finer Than
Clast Size (mm)
0
10
20
30
40
50
60
70
80
90
100
0
5
10
15
20
25
30
35
40
45
50

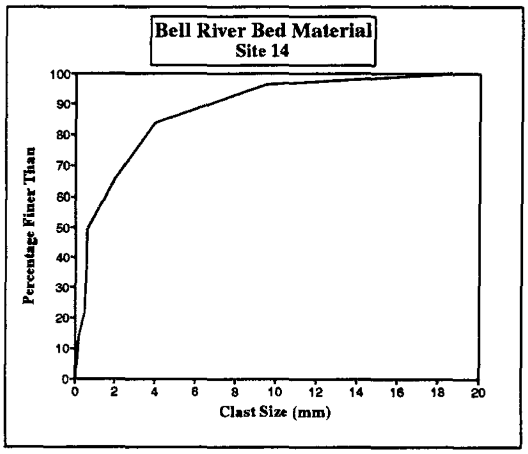

Bell River Bed Material
Site 9
Percentage Finer Than
Clast Size (mm)
0
10
20
30
40
50
60
70
80
90
100
0
20
40
60
80
100
120
140
160

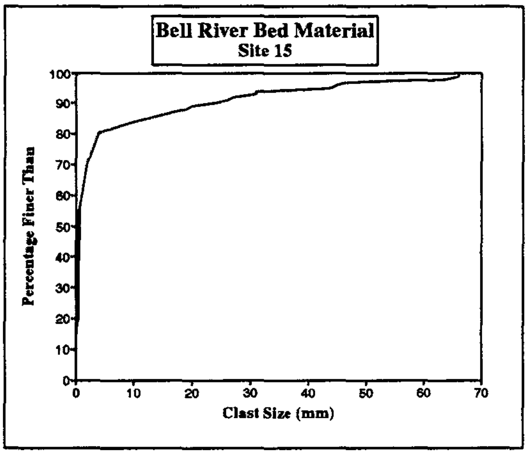

Bell River Bed Material
Site 10
Percentage Finer Than
Clast Size (mm)
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
250

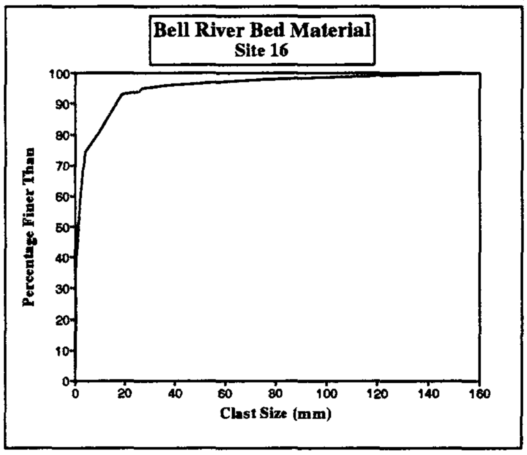

Bell River Bed Material
Site 11
Percentage Finer Than
Clast Size (mm)
0
10
20
30
40
50
60
70
80
90
100
0
20
40
60
80
100
120

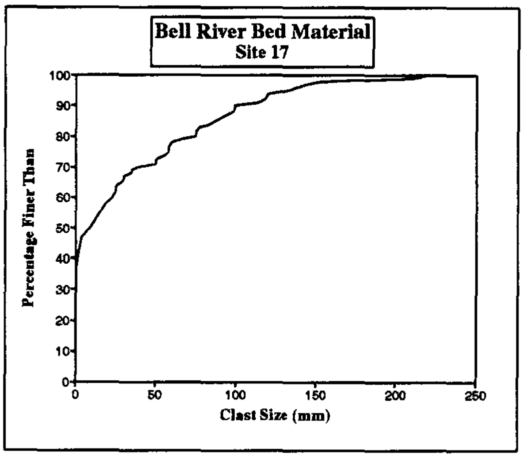

Bell River Bed Material
Site 12
Percentage Finer Than
Clast Size (mm)
0
10
20
30
40
50
60
70
80
90
100
0
10
20
30
40
50
60
70


Bell River Bed Material
Site 13
Percentage Finer Than
Clast Size (mm)


Bell River Bed Material
Site 14
Percentage Finer Than
Clast Size (mm)


Bell River Bed Material
Site 15
Percentage Finer Than
Clast Size (mm)


Bell River Bed Material
Site 16
Percentage Finer Than
Clast Size (mm)


Bell River Bed Material
Site 17
Percentage Finer Than
Clast Size (mm)

APPENDIX E

BELL RIVER FARMERS QUESTIONNAIRE

RIVER CHANNEL CHANGES IN THE BELL RIVER, NORTH EASTERN CAPE

BELL RIVER FARMERS QUESTIONNAIRE

Please fill this questionnaire in as thoroughly as possible. You may remain anonymous if you choose to. Information will not be used for any other purposes other than research.

1) Name (optional)

2) What farm do you live on?

3) How many farms do you own?

4) What date were your farms originally established?

Farm Number	Date Established

5) What date did you purchase these farms?

Farm Number	Date Purchased

6) What are the sizes of the different farms?

Farm Number	Farm Size (Ha)

7) How long have you (your family) lived in the Rhodes area?

8) Have you noticed any channel changes in the Bell River on your farm?

	NONE	SLIGHT	MODERATE	SEVERE
Channel Deposition				
Overbank Deposition				
Reduced Pool Depth				
Cutoff Meanders				
Flood Plain Scour				

Other (specify)

9) What do you think are the reasons for this change?

10a) Have you planted any trees on the river banks?

YES	NO

10b) If yes, when did you plant these trees?

11) What type(s) of trees did you plant?

12) Have these trees

	YES	NO
Increased In Number Along The Bank		
Stabilized The Bank		
Blocked The Channel		

Other

13) How much stock do you have on each farm at present?

FARM NUMBER	SHEEP	CATTLE

14a) Have your stock numbers increased or decreased in the years that you or your family have been farming?

YES	NO

14b) Has there been any long term change in stock numbers?

YES	NO

(Comment)

15) Can you supply stock numbers since you started farming?

FARM NUMBER	YEAR	SHEEP	CATTLE

16) What grazing strategy do you use?

17) Has this strategy changed over the years?

YES	NO

(please specify)

18) How often do you burn your veld?

19) Has your burning regime altered?

YES	NO

(please specify)

20) When were your farms fenced?

FARM NUMBER	DATE FENCED

21) What is the erosion status of your farms?

FARM NUMBER	NONE	SLIGHT	MODERATE	SEVERE

22) Has erosion increased or decreased since you have occupied your farms?

YES	NO

(Comment)

23) Has your veld condition improved since you occupied your farms?

YES	NO

24) If yes, what is the reason for this improvement?

25) Have you noticed any recent erosion features on your farm?

YES	NO

(please specify)

It would be helpful to know if the following information were available

Do you measure rainfall, if yes, how long have you been measuring for?

Do you have any relevant historical documents which could be consulted (e.g. diaries, stock records, photographs)
If you do possess such material would you permit their examination?

Thank you for your co-operation