High magnitude flood deposits of the Kuiseb:

an analysis of driftwood deposition

on an ephemeral river

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Undergraduate Dissertation
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January 1996

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Acknowledgements

Staff at Gobabeb Desert Research Station

Juliana Ziedler

Mary Seely

'Snake' for help with equipment and transport

Pieter Mostert

●

Dr. S. Stokes

Mr. D. Anderson

Friends and relatives for proof reading

Julian Martin

Karen Gidwani

Frank Eckhart for advice and photographs

●

For Financial Support:

Jesus College, Oxford

Oxted County School

Clarence Sanders Trust Fund

Percy Gibson

Titsey and District Rotary Club

Oxted Rotary Club

Mr. and Mrs. Steven-Fountain

Barclays bank Oxted

Flood deposits of the Kuiseb: an analysis of driftwood sedimentation on an ephemeral river

SoG 31

ABSTRACT:

Fluvial deposits are not merely limited to inorganic sediments. The high energy events such as large floods can rip out living trees or carry away dead ones during flow. The impact on the ecosystem may be devastating, but the deposits left behind can be very informative and help to infer past, present or future flood flows. The desert environment of the Kuiseb river, Namibia, provides and incongruous setting for the study of high magnitude floods and deposition of large tree parts. However, driftwood left behind by this river is widespread and can be impressive in size of logs and number found in a small area.

The aims of this study were to investigate whether there was a pattern in the distribution of the driftwood, to explain the distribution with reference to four hypotheses and to draw tentative conclusions as to the causes of the distribution. The hypotheses were that channel constrictions, channel widenings, bends or partial damming by linear dunes caused the deposition.

The principal methods of investigating these aims involved surveying a 15k reach of river by a transect method and recording the location of logs exceeding an arbitrary 4cm diameter cut-off point. Location was recorded from surveying and pacing data. These results were used to create a contour plot of wood intensity for total, and 'large' wood, a stylised map of the deposition along the channel.

The influence of channel widenings was researched by a combination of measuring channel width in the field, measurements from maps and aerial photographs, and surveying to 100m either side of the channel, to create a contour plot of morphology, this gave an impression of channel widenings at a flood stage. Constrictions were investigated by using the same data, augmented by recording occurrence of bedrock outcrops in the field. Bends were studied from map and aerial photograph data alone, one dimensional series analysis of the stream trace was used to identify the position of bends and straight reaches of channel. Partial dune damming was look at through dune proximity to the channel in the field. Rates and direction of movement were found from secondary data sources and a risk map of dune damming areas drawn.

Qualitative correlation of areas of high intensity deposition and the location of each of the causal features was first undertaken. Descriptive statistics were used to verify the patterns. The main findings were that there was little pattern in deposition wood, no discernible difference between north and south banks, little deposition in the channel and beyond 300m from it. Longitudinally, no real pattern are three main areas of deposition, at the Weir, Soutriviere and at transect 35. Qualitative assessment revealed little about the relationships. Correlation coefficients and a Mann-Whitney U test revealed that dunes and constrictions had to be rejected, although widenings and bends were possible causes of the distribution

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CHAPTER 1: INTRODUCTION

1.1 Ephemeral rivers and depositional processes

1.1.1 Ephemeral rivers

"Stream channels are among the most dynamic components of the landscape" (Williams and Costa, 1988). Rivers are important features of both human and natural spheres, providing a possible water source, transportation medium and in many places a way of defining boundaries. Within geomorphology they take on a great significance as one of the most effective agents of erosion and deposition (Knighton, 1984). Even when energy input to the fluvial system is low, for example in arid zones where precipitation input is defined as 250 mm p.a. or less (Thomas, 1989), erosion and deposition can still take place.

During a flow event, dryland rivers may even be more efficient geomorphic agents than their perennial counterparts of a similar size (Graf, 1988). They are often ephemeral flowing in response to storm events (Graf 1988). The flood hydrograph is normally associated with a short lag time, a steep rising and recession limb, depicting the bore and with high transmission losses respectively (Renard and Keppel, in Graf, 1988). The flashy variable regime and high transmission losses are partially responsible for the characteristic high width / depth ratio (Graf, 1988; Baker 1988), and for the typically convex long profile (Thomas, 1989)

Modern fluvial geomorphology has its roots in these dryland systems. The exploration of the arid American west provided a major starting point for sustained research into river process. It is generally accepted that the work of G. K. Gilbert in the Henry mountains of Utah initiated much study (Gilbert, 1877 in Baker *et al.*, 1988) which was continued in particular by Leopold (Cooke *et al.*, 1993). Contributors to geomorphic research are still made in these areas, by such workers as Schumm, Graf, Bull, and Maddock (Baker *et al.*, 1988), in conjunction with parallel investigations in Israel under Schick and by Yair and Gerson (Abrahams 1994).

A rise in process studies within geomorphology focusing on perennial rivers, dryland studies being concentrated only on processes peculiar to those areas, limited rainfall and discharge data for arid areas and expense of field work have all been accused of being responsible for the lack of fluvial research in arid regions in recent years (Thomas, 1989). Research on ephemeral rivers has instead been concentrated on semi-arid areas where there are more flow events to study (Leopold and Miller, 1956, Thornes, 1969). This has left a current dearth of information concerning arid zone rivers. This is unfortunate as the study of these systems can offer practical benefits of flood prevention and land protection, and the academic benefits of models of channel flow.

1.1.2 Sedimentation

The most important aspect of a river to the geomorphologist is the transport of sediment (Chorley *et al.* 1984). Dryland rivers have proportionally high sediment loads, thought to be due to unconsolidated or unvegetated banks; typically up to five times that of a perennial river of equivalent size (Graf, 1986). Processes of sediment transferral follow a tripartite division into erosion, transportation and deposition.

Deposition is one of the most highly investigated (Lewin, 1988) and will be focused on here. Often the only surviving evidence of fluvial processes are the deposits themselves (Baker 1988 and Leopold *et al.* 1964): the analysis of these is not only important for inferring future geomorphological processes, such as Waythomas' (1994) identification of floods in the stratigraphic record of Arthurs Rock Gulch, Australia but may also be important for engineering predictions of 100 year floods (Costa, 1974).

Deposition of a particle occurs when the flow velocity becomes lower than the fall velocity for that particle, as defined by its shape, size and density and the viscosity and density of water (Summerfield, 1991). This velocity is obviously lower than that required to initially entrain the particle. The largest particles will be deposited first in any slowing of velocity. Given particular flow and sediment load characteristics, whole reaches of river may be aggrading or eroding at a particular point in time. However, there is still a large part for other more localised conditions to exert a control.

> "Conditions on a channel bed can change rapidly over time and space, so whether sediment is entrained or deposited depends on local rather than average conditions" (Summerfield, 1991 at page 215).

Discharge, density of water, channel slope and velocity (Summerfield, 1991) are thought to be the main local conditions of note, Reineck and Singh (1980) would add turbulence. These are governed by factors both external and internal to the system, and in turn control the local energy environment of the reach (Lewin, in Calow 1992).

These depositional processes produce varied geomorphological forms. Flood flow deposits are not unlike these normal flow deposits, although they are more often associated with overbank deposition and the construction of a floodplain. Dryland rivers tend not to lay down a floodplain in the strict sense of the word (Graf, 1988). They do, however, leave their channels to inundate surfaces next to them, forming a zone of composite fluvial landforms, (Cooke *et al.* 1989). Patterns of sedimentation here are governed by the same factors, velocity may be highly varied across the floodplain (Popov and Gavrin 1970;Velikanova and Yarnykh 1970), causing spatial differentiation in deposits. Channel processes may also affect floodplain deposition: Richards (1982) shows how channel pattern (itself affected by cross sectional form) affects deposition.

The analysis of depositional features has tended to concentrate on size distribution, directional properties and internal structures, (Lewin in Calow, 1992). There has been little work on spatial and temporal patterns in which sediment actually produces depositional features like floodplains; what is known tends to be concentrated in a few types of environment, and the pre-Holocene time period (Lewin, 1978).

1.3 Biogenic sediments: plant macrofossils

Fluvial deposits are not merely limited to the inorganic sediments. Plant debris is eroded and deposited in a similar way to inorganic material (Keller and Swanson, 1979). Erosion may be understated or spectacular as in the floods of 1967 when many living trees were uprooted from the banks of Bijou Creek, Colorado (Mckee *et al.* 1967). Deposited organic material can provide useful information regarding conditions of sedimentation (Reineck and Singh, 1980) and through radiocarbon dating may be used to infer past and present fluvial processes.

Organic deposits are particularly important in sediment limited areas, where debris like driftwood may be the largest clast size available for erosion and deposition. The extreme aridity of areas of the globe such as the Namib ensures the preservation of such features and prolongs their useful life as interpretative features. Vogel (1989) documents how dead trees in the Namib may remain upright for many centuries. Plant macrofossils could also give an insight into the operation of the poorly understood (Graf, 1988) transport mechanism of flotation. Knowledge of the depositional environment governing the emplacement processes of plant macrofossils could be vital when investigating sediment sequences. Environmental reconstructions of past environments rely on such material to radiocarbon date particular deposits, greater understanding could enhance environmental reconstructions themselves, and possibly help to avoid errors in interpretation of inorganic deposits (Baker *et al.*, 1977). Baker and Kochel (in Baker *et al.*, 1977) show how large organic debris such as tree logs can be especially important in interpreting slackwater sediment sequences, as they provide a material to radiocarbon date, and allow the absolute chronology of river sediment history to be established.

1.2 Aims:

This study originated from a parallel interest in arid zone fluvial geomorphology and the Namib area. Within the wider field of fluvial geomorphology this study is concerned with the depositional features of large floods and the processes which control the spatial distribution of these features. I was offered the chance to undertake my fieldwork at the Desert Research Foundation of Namibia's research station at Gobabeb, in the Namib. Using this institution as a base, this research was conducted on the nearby Kuiseb river, focusing on the deposition of driftwood in the area during high magnitude flood events. It was suggested that large deposits of driftwood were brought down in major floods , and deposited as far away as 200m from the river channel. The explanation of spatial variation in these deposits has been difficult to decipher, but speculation suggests a connection channel widenings, channel constrictions by bedrock, channel bends and partial dune damming of the river.

The aims of this study are threefold:

(a) To identify spatial patterns in the distribution of driftwood.

(b) To explain this distribution with reference to four hypotheses:

Distribution is related to cross sectional widening

Distribution is related to channel constrictions by bedrock

Distribution is related to river bends.

Distribution is related to partial damming of the Kuiseb by migrating dunes.

(c) To draw conclusions as to the cause of the distribution.

1.3 Location:

1.3.1 The Namib desert:

The study took place in the Namib desert: a relatively narrow tract of land 2 000 km long (Huntley, 1987) and between 80 and 140 km wide (Goudie, 1972). The area covers 270 000 km^2 of Namibian coast (Huntley, 1987). It is bounded to the south by the Olifants River (South Africa) and to the north by the Carunjamba river Sao Nicolau (Mocamedes district, Angola) (Ward *et al.*, 1983) (see fig. 1.3a).

The prevailing climate of the area is arid to extreme arid. The desert conditions are linked to the descending limb of the Hadley cell and resultant South Atlantic Anticyclone at the tropic of Capricorn, to the cold northward flowing Benguela current (fig. 1.3a and photograph 1.3a) and to the divergence of trades along the coast. The area to the north of the Kunene river (see fig. 1.3a) receives maximum rainfall in summer. To the south rains occur between October and May, when the Inter Tropical

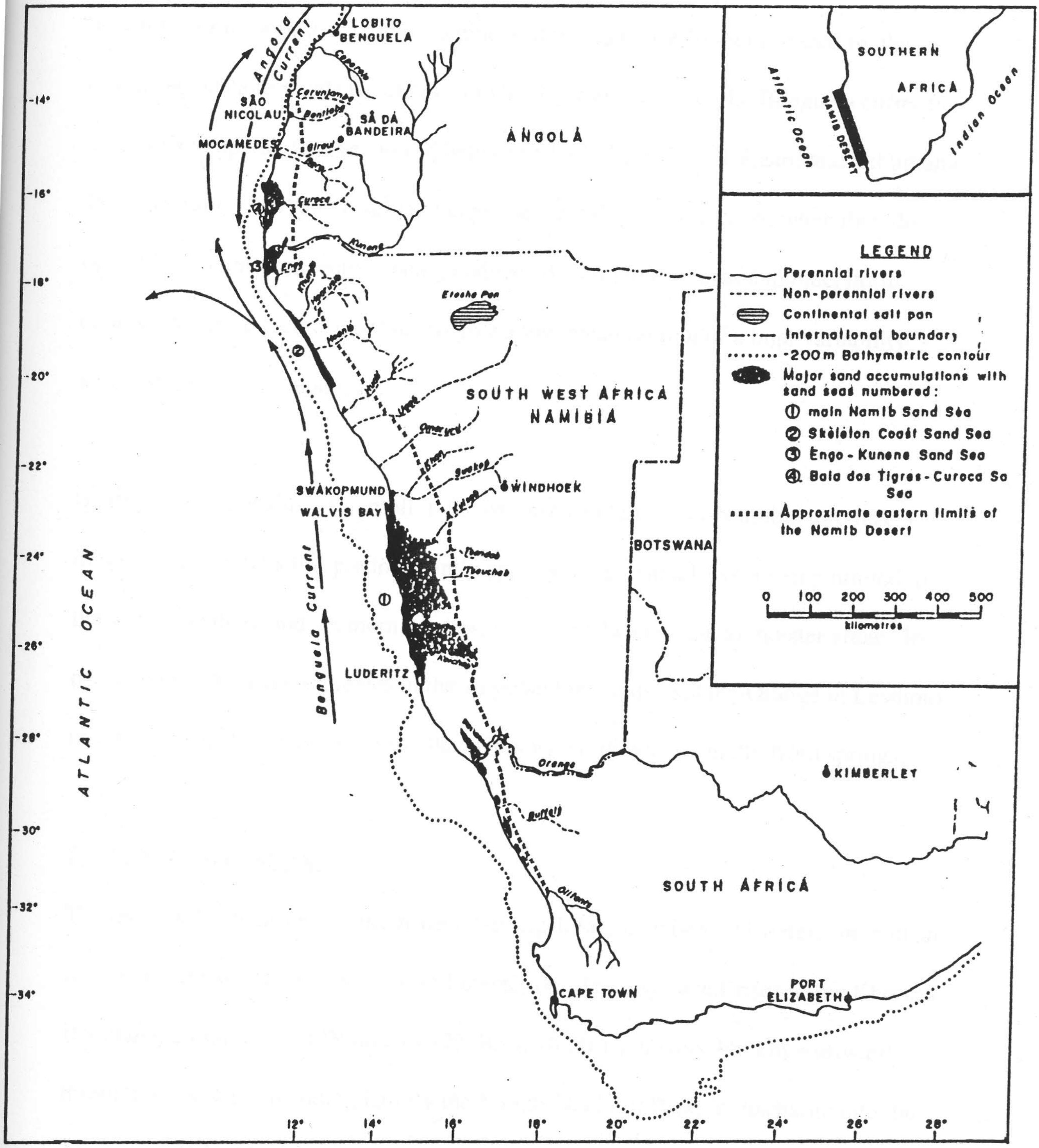


Fig. 1.3a Map of the Namib Desert and Environs. (Source: Huntley, 1987)

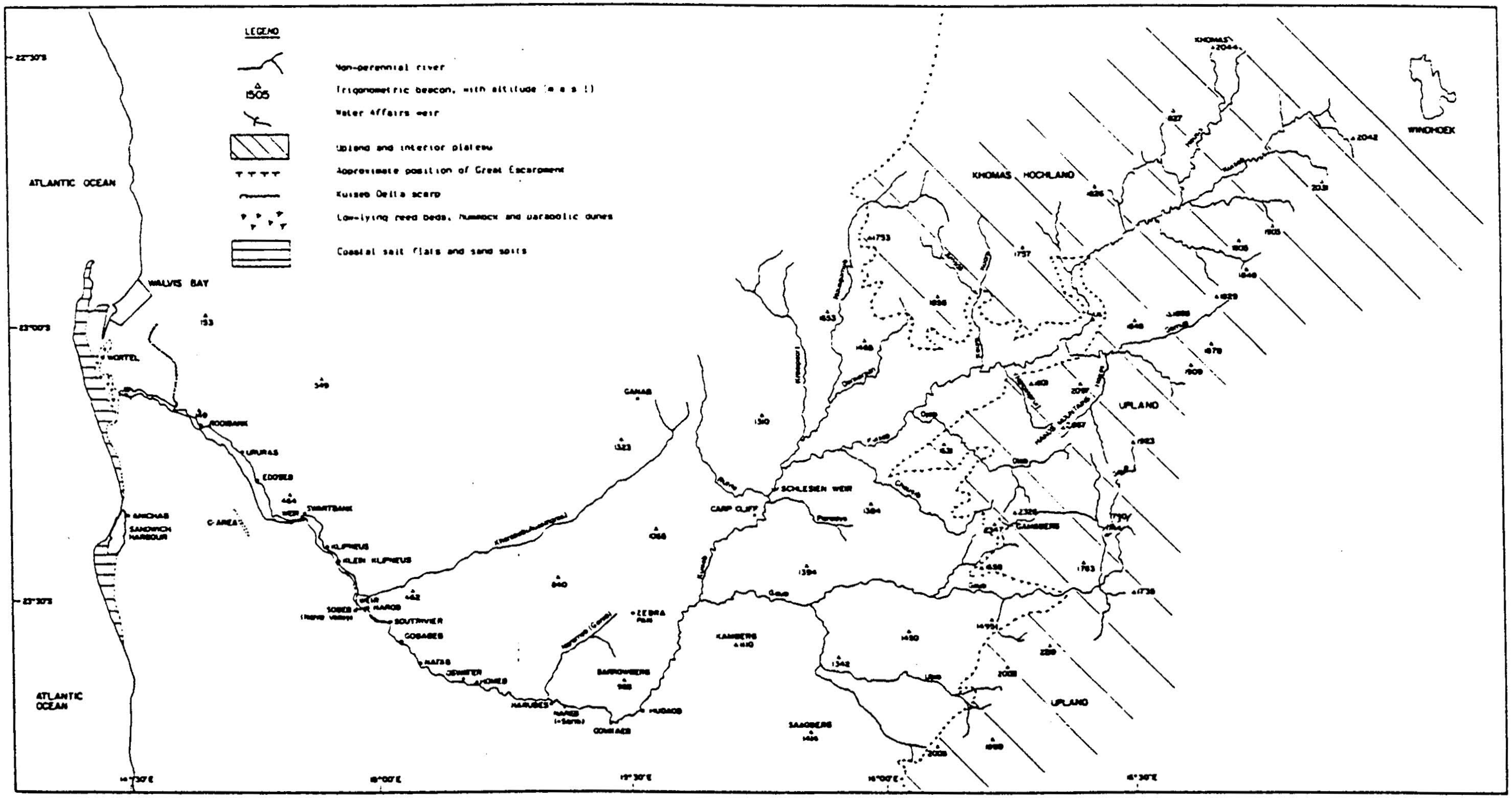
Convergence Zone and therefore high pressure system in this area move north, allowing more moist air, originating form the Indian Ocean, to enter from the east. Even this brings only limited rain, owing to the drying effects of the air masses moving over most of the African continent. Rainfall is still further reduced by the prevailing onshore winds which are cold having travelled over the Benguela current, creating a temperature inversion of between 610 and 1 830 m (Taljaard and Schumann 1940 in Brain, 1984) and resultant heightened stability. These rains, when they do occur, are mainly convective, being connected with large localised thunderstorm clouds. All these factors combine to give a low mean rainfall of a high variability - up to 50% per in some areas.

Aridity and seasonality of rainfall in the western catchments of Namibia produce a drainage system which is predominantly ephemeral, perennial rivers being limited to the wetter northern and southern borders, where headwaters rise in moister areas. In particular the Kunene originates in the Angolan highlands, and the Orange in Lesthoto (see fig. 1.3a). There are some smaller rivers which flow perennially from springs.

1.3.2 The Kuiseb catchment:

The river under analysis was the Kuiseb (see fig.1.3a), an ephemeral watercourse in an arid area, with significant biogenic sedimentation. The river itself rises in the Khomas Hochland, 24 km west of Windhoek (22^{0}40‘S, 16^{0}50‘E), travels 440 km westward through the Namib, including latterly the Namib-Naukluft Park, to discharge into the Atlantic at Walvis Bay (23^{0}10‘S, 14^{0}30‘E) (Seely *et al.*, 1979) (see fig. 1.3b). The main ephemeral stream makes its way through the steep sided bedrock canyon, on a

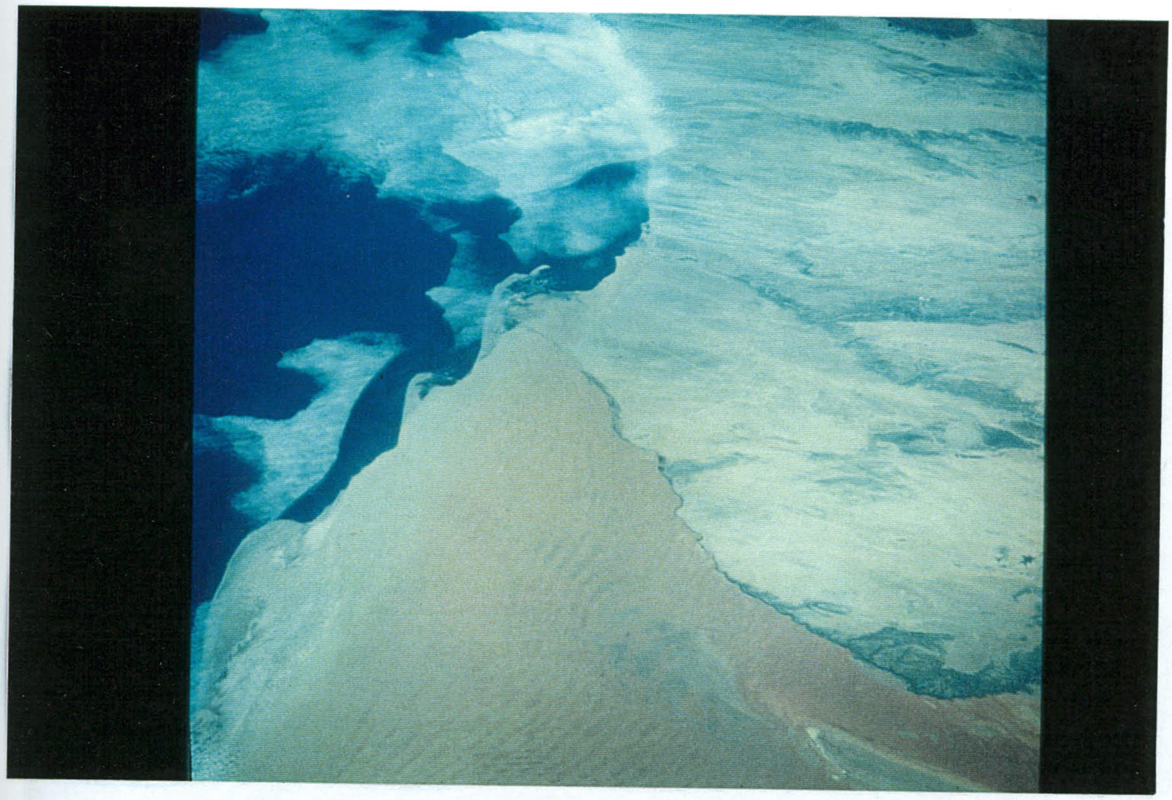
Fig. 1.3b The Kuiseb River basin, indicating major physiographic regions
(Source: Huntely 1987)



south westerly course dividing the dune and gravel Namib as it emerges from the headwaters (see photographs 1.3a, d and 1.3e). At Hudaob, the river changes to a north-westerly course and flows in an alluvial bed with occasional bedrock outcrops. 5 km downstream from Rooibank sand occurs on both banks; the river here splits into northern and westerly branches to form a delta, the northern arm of which was cut off in 1961 at 'mile 16' to prevent flooding of Walvis Bay.

1.3.3 Geomorphology and geology of the Kuiseb catchment:

Marker (1977) Divided the Kuiseb into four geomorphological sections based on valley morphology. The 'Headwater Section' is incised shallowly into the former planation surface of the Khomas Hochland (Spreitzer 1966 in Marker 1977) (see photograph 1.3b and 1.3c). The 'Canyon Section', extending from the highland to Homeb, is more severely incised through a calcrete fanglomerate into the underlying bedrock. Maximum incision occurs in the Kuiseb Canyon between the Kuiseb-Gaub confluence (see fig. 1.3b) to approximately 5 km upstream of Homeb, at Hudaob valley depth exceeds 200m. the lower canyon section between Homeb and Gobabeb includes visible bedrock but the valley here becomes more open and less pronounced. The section between Gobabeb and Swartbank Marker calls the 'Valley Section'. Here the river is still clearly defined but valley depths are generally less than 10m. The channel is indistinct in the 'Plains Section' between Swartbank and Rooibank, owing to a less coherent deposit, and between Rooibank and Walvis bay there is no valley at all.



Photograph 1.3a Namib boardering Atlantic Ocean
Kuiseb dividing dune and gravel Namib
Photograph courtesy of Frank Eckhardt

Photograph 1.3b Kuiseb incising into schists of the Khomas Hochland

Photograph 1.3c Headwater section of the Namib near the Kuiseb bridge

Photograph 1.3d Thickly vegetated Kuiseb dividing the dune and gravel Namib at Gobabeb

Photograph 1.3e Meandering Kuiseb, dividing dune and gravel Namib
Gobabeb Research Station to Left Hand Side

The Kuiseb exhibits a valley-in-valley cross section and convex long profile as is common with many ephemeral rivers as energy decreases towards the mouth, within this there are several knick points characteristic of a change in base level. These changes in base level have lead also to hanging Wadis like the Soutrivier, where the wash level cannot keep pace with the incising river. Throughout these changes in base level the Kuiseb has maintained its course for much of the Cenozoic, unlike the Tsondab and other Namib rivers (Marker, 1977).

Table.1.3a shows and outline geomorphological history of the central Namib in the Kuiseb region and figure 1.3c a simplified geological map. During the Pre Cambrian sedimentation and metamorphosis of the Basement Complex rocks, namely Damara system schists, marbles and Salem granites occurred (Marker 1977 , Ollier 1977). Interspersed within this complex Karoo age dolerite dykes (Clifford 1967, Martin 1965 in Marker 1977, Ollier 1977). Prolonged erosion planed these rocks down to the base level of the newly developing South Atlantic Ocean (Martin 1973 in Huntley, 1987). Ollier (1977) has named this the "Namib Unconformity Surface". The basal conglomerate and the Tsondab sandstone were deposited on this basement. The basal conglomerate, on the south side of the Kuiseb, near Hudaob comprises angular quartz fragments and basement garnets. The Tsondab sandstone, a quartz sandstone cemented by carbonate, is characterised by widespread palaeodunes indicating a wind regime similar to that of today. The third period of land formation involves fluvial incision and a cut and fill sequence (Ollier 1977). Downstream from Homeb there are remains of a river terrace preserved in cemented gravels, a deposit called the Ossewater conglomerate. Then came period of aggradation and the deposition of the

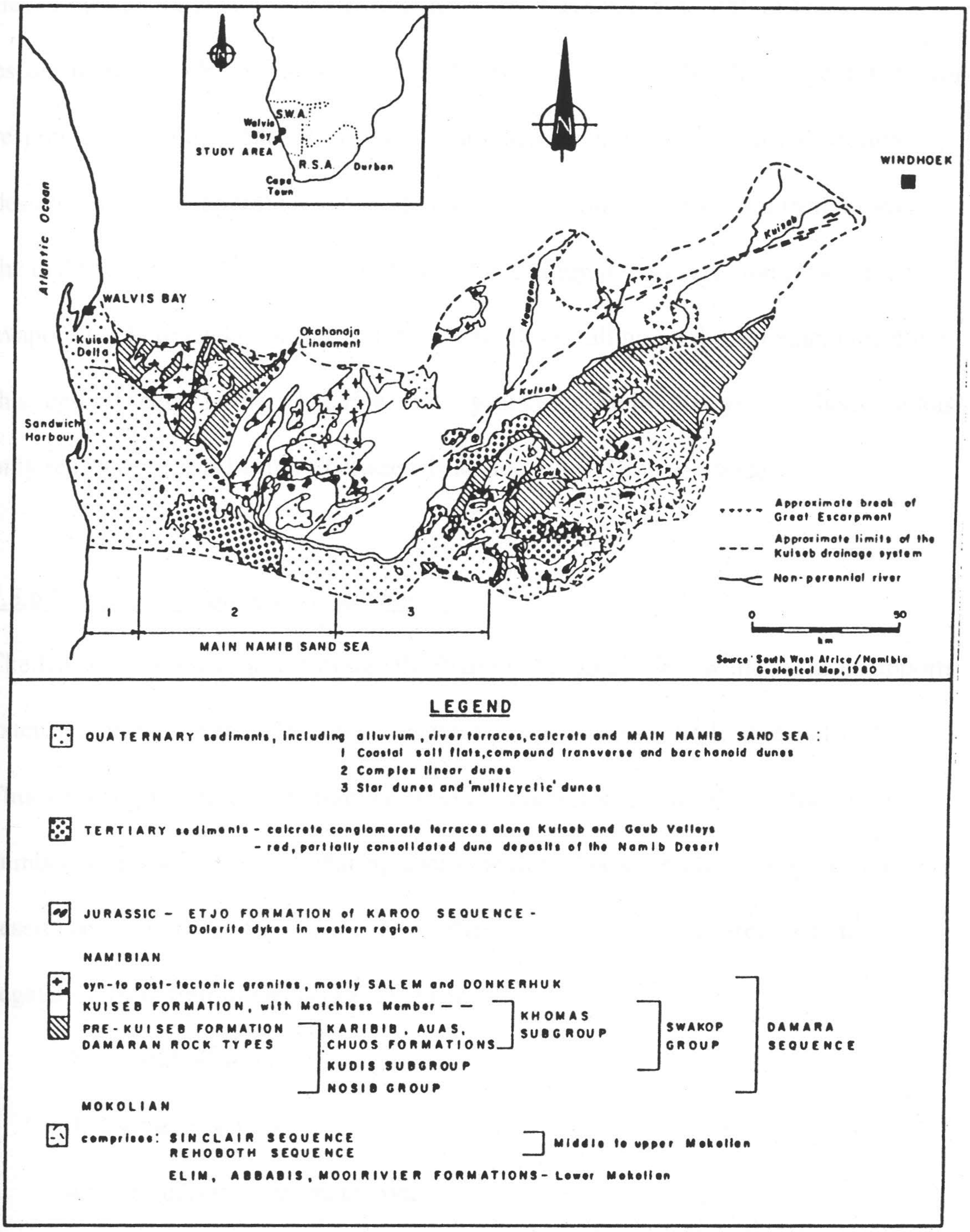
Homeb silts, there was then reexcavation to bedrock, formation of the lower and minor terraces of the Kuiseb.

KUISEB	
10	Deposit Young terrace gravel and
9	Erode to river level
8	Deposit Homeb silts
7	Erode to present river level
6	Deposit Ossewater conglomerate
5	Erode almost to canyon bottom
TSONDAB	
8	Deposition of the modern dune field
7	Erode to Vlei leaving the 50m terrace
6	Erode to 50m level
5	Deposit gravels from the East
4	Erosion of the Tsondab Planation surface
3	Deposition of the Tsondab Sandstone
2	Deposition of the Basal Conglomerate
1	Formation of the Namib Unconformity

Table 1: Outline geomorphology of the central Namib (Ollier 1977)

1.3.4 Climate of the Kuiseb catchment:

The climate of the Kuiseb drainage basin, as the rest of the Namib, is arid to extreme arid. There is an east-west rainfall gradient (see fig.1.3d.) from 400mm pa in the eastern highland to 20mm at the coast. Rain is highly variable both spatially and temporally.(Dealy *et al.*, in Dausab, 1989). Moisture is augmented by fog precipitation occurring on 60 days pa at Gobabeb. 83% of rainfall evaporates therefore only 17% reaches the land (Johnson *et al.*, 19) Temperatures are less variable, with a mean of 24.2^0C at Gobabeb in March and 17.7^0C in July. Eastern and Southerly winds prevail in Winter, with mean velocities of 21 km/hr, in summer there are lower velocity winds from the north west.



Source: South West Africa/Namibia Geological Map, 1980

Fig 1.3c Simplified Geological Map of the Kuiseb drainage system
(Source: Huntely, 1987)

1.3.5 Hydrology of the Kuiseb catchment:

The Kuiseb catchment drains an area of 14 700 km^2 (Huntley, 1987) 80% of which lies in the area of higher rainfall in the Khomas Hochland (100-400mm) and escarpment zone (50-100 mm, Seely *et al.* 1979)(see fig. 1.3.d). Discharge in the river responds to rainfall events. It increases with distance in the upper canyon section despite the high evaporation losses. In the lower section, downstream from Gorob, the bed becomes alluvial. The combined effect of higher transmission losses and evaporation here lead to only 1 to 1.5% of the water falling on the Hochland reaching this region (Seely, 1979). The river flows past Gobabeb in most years although it has only reached the sea 14 times between 1830 and 1980 (Braune, 1992).

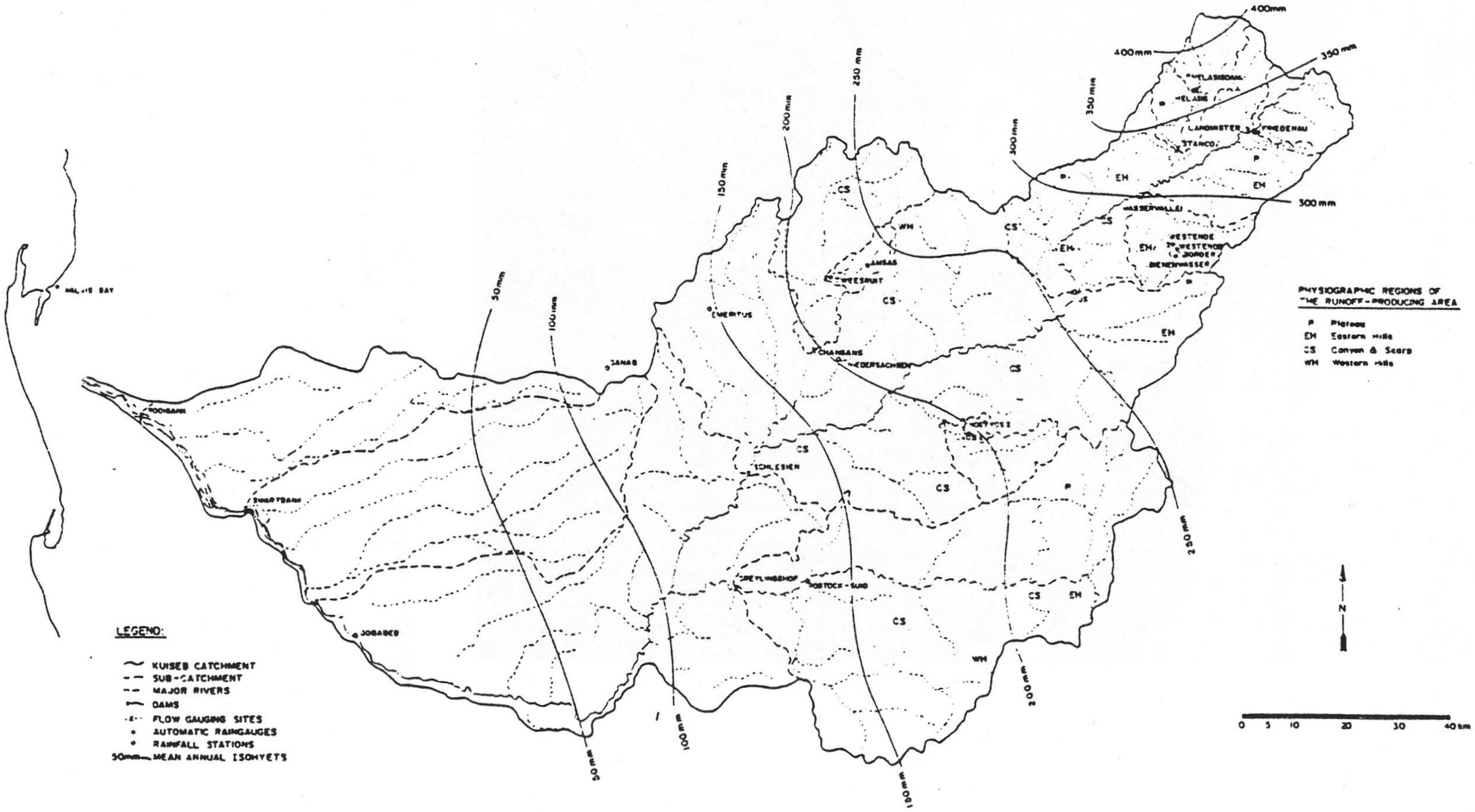
1.3.6 Vegetation of the Kuiseb catchment

The Kuiseb is a linear oasis through the Namib, the aquifer below the surface supports extensive growth of trees and other vegetation (see photographs 1.3d, e and 1.3f). This semi-tropical forest community provides water, forage and shelter for a vast number of species, especially during aperiodic droughts, even allowing some non-desert species to range far into the desert (Seely, et. al 1979). The area includes vegetation from four of Geiss (1971) classes:

2. Central Namib
3. Southern Namib
4. Semi-desert escarpment zone
8. highland savannah.

Differences within these communities occur not so much upstream - downstream as from channel to floodplain. The lower Kuiseb between Homeb and Rooibank (see fig.

Fig 1.3d Rainfall and runoff over the catchment area of the Kuiseb
(Source: Huntely, 1987)



Photograph 1.3f Semi-tropical riverine forest on Kuiseb banks
Photograph courtesy of Frank Eckhardt

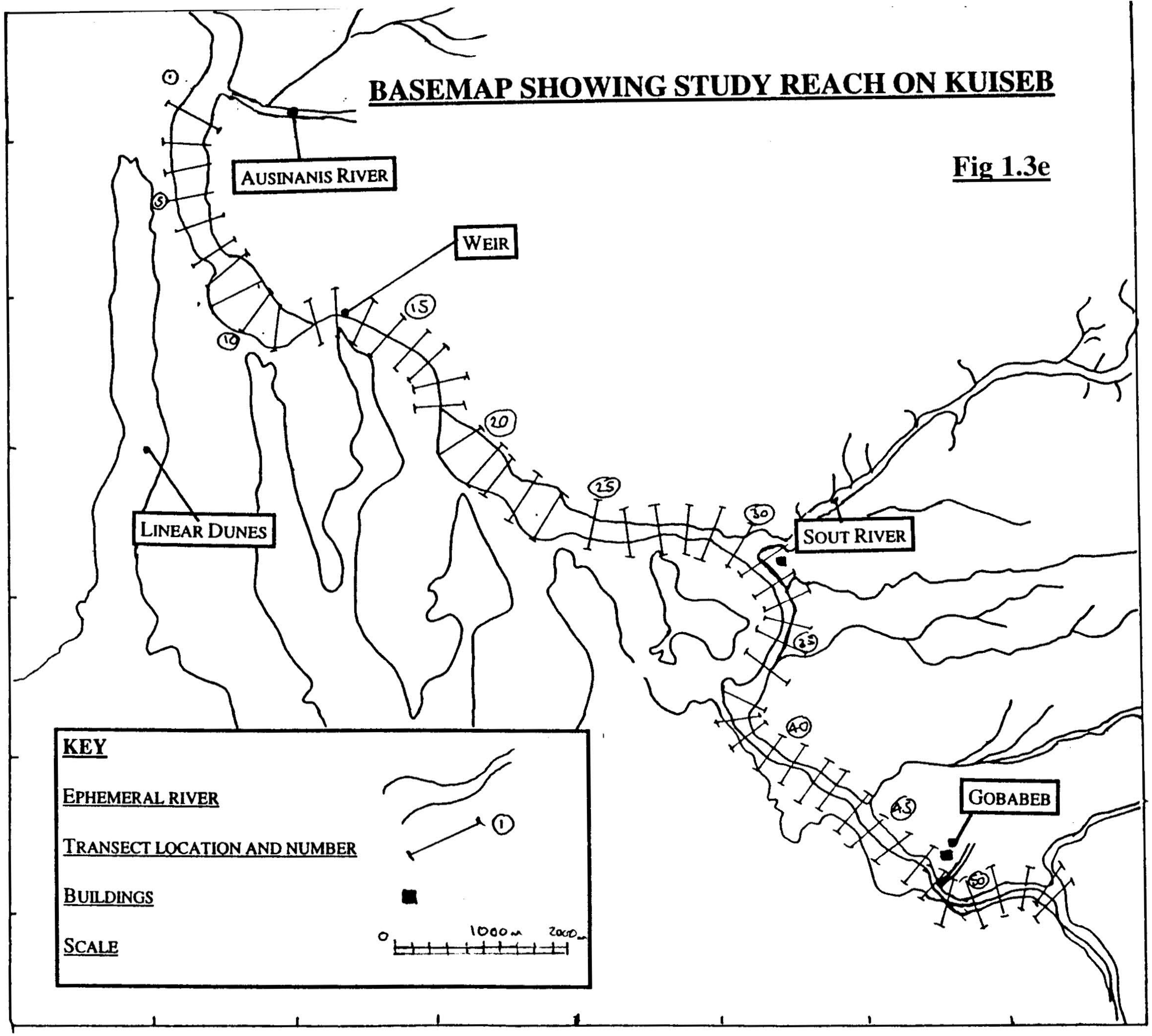
1.3b) has a well developed riverine vegetation community (Breen and Ward 1983), supporting at least 10 species of perennial plants of which *Acacia Albida* 21%, and *Acacia Erioloba* 44%, are the principle components (fig. 1.3g shows the vegetation composition of the lower Kuiseb). Recently these have come under threat from heavy extraction upstream and prolonged droughts (Ward, in Huntley, 1987).

Species	**Occurrence (%)**
Acacia Albida	21
Acacia Erioloba	44
Tamarix Usneoides	12
Salvadora persica	2
Phoenix Dadylifera	0.8
Ficus sycomorus	0.4
Ficus cordata	0
Maerua schinzii	0
Acanthosicyos horrida	8

Table 2. Species composition of the Lower Kuiseb (Seely *et al.* 1980)

1.4 Location of study

Fieldwork was undertaken over a 15 km section of the Kuiseb, between Dassie Rock and Ausinanis wash shown on the basemap (fig. 1.3e) and satellite photograph (fig. 1.3f). This area comes under Marker's (1977) 'Valley Section', and encroaches a little on the 'Canyon Section'. This area provided an ideal site to study driftwood sedimentation, the low channel banks and high tree density gave a good sediment source and an effective depositional environment. The region is one of the most accessible for the desert section of the Kuiseb, as it lies close to the Desert Research Station at Gobabeb. Unlike most ephemeral watercourses this area of the Kuiseb has



BASEMAP SHOWING STUDY REACH ON KUISEB

Fig 1.3e

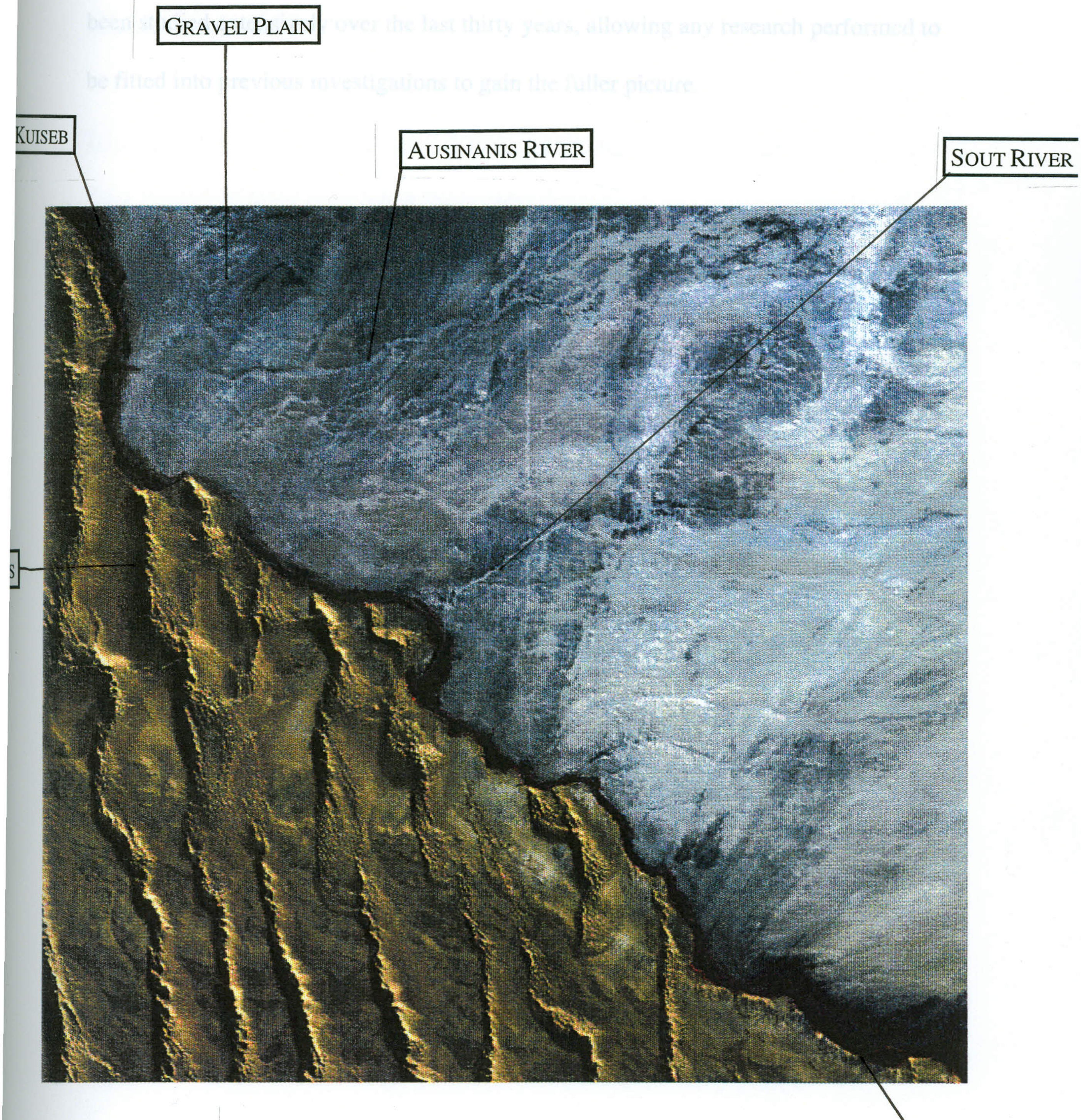


Fig 1.3f Satelite image showing study area

been studied extensively over the last thirty years, allowing any research performed to be fitted into previous investigations to gain the fuller picture.

CHAPTER 2: FLOODS

2.1 Flood research: An important aspect of fluvial geomorphology

2.1.1 Paucity of flood research in the present day

> "There remain vestiges of concern that the immense power and energy of extraordinary floods are something to be downplayed" (V. R. Baker in Baker *et al.*, 1994).

Baker notes a lack of investigation into the geomorphic action of floods within current inquiry. This contrasts with the high amounts of flood work within fields such as socio-economics, engineering hydrology and land-use planning (Baker, *et al.*, 1988), Ward 1978). Recent efforts to study flood events have been from the socio-economic and human impact side of the spectrum, with parallel initiatives in the USA, Great Britain and Russia. Ward notes how floods often make news within a population, whether they are small or large scale events. Classical literature also attaches great importance to the study of extraordinary floods (Hazen 1930 in Baker, 1988). Baker wonders why modern traditions in geomorphology have moved away from this.

There are numerous reasons why modern geomorphological study of floods has received comparatively little attention. A large component may be the vestiges of a dubious scientific past for flood studies (Baker *et al.*, 1988), with roots in the biblical-catastrophist views of the seventeenth and eighteenth centuries. Here all events on the earth's surface were reconciled to catastrophic events like the Noachian flood. The reaction to this was the Victorian school of gradualism during the nineteenth century, forefronted by such workers as Playfair, Hutton and Lyell. Here fluvial processes were seen as gradual and ordered, there being no place in studies for flood events. More recent work in fluvial geomorphology has been heavily connected with the use of computer modelling and statistical prediction of events. This has downplayed flood events, firstly as data for high magnitude events are sparse not providing a reasonable sized sample population. This leaves high magnitude data appearing as an outlier and high events become concealed as merely anomalies whilst data is extrapolated from lower magnitude events. The use of statistics is justified by the fact that fluvial systems are exceedingly complex and can only be understood or predicted with reference to mathematical analysis. The use of computer as an alternative to fieldwork has also characterised the past two decades (Baker *et al.*, 1988). As a result there had been a tendency to develop models based on theoretical ideas of high magnitude events rather than empirical data.

The Fourth possible reason for the neglect of floods concerns magnitude and frequency debate. Wolman and Miller (1960) established that low magnitude high frequency events perform more geomorphic work (in terms of sediment transfer), in humid temperate areas, than high magnitude low frequency events.

> "The major work is accomplished during the more modest but relatively frequent floods rather than the larger but rarer catastrophic floods" (Leopold *et al.*, 1964 in Ward, 1978).

On a short to medium timescale the forms and processes which created them tend towards an equilibrium. Therefore there seems to be more reason to study lower flow events, and this is enhanced by the ease of undertaking fieldwork in such cases.

The importance of larger floods does in fact only emerge when the concept of geomorphic work is examined. Wolman and Miller (1960) defined geomorphic work in terms of sediment transferral, however, Wolman and Gerson (1978) revised the concept as one of geomorphic effectiveness, the landforming agency of processes. The modification of landforms often requires the exceeding of a threshold (Schumm 1977 extrinsic threshold), this is not possible for small events no matter often they happen. Gupta 1983 gives a good example of how floods can play a larger role than once thought in modifying landforms, on a permanent basis.

In fact geomorphic systems are not this simple, they contain threshold response and obey non-linear processes, often only within the rules of catastrophe theory (Abrahams 1994). Newson (1980) points out the new ideas of recovery time, thresholds and complexity in the system.

2.1.2 Flood events:

Ward (1978) has compiled three general definitions of flood events. A relatively high flow which overtaxes the natural channel provided for the runoff (Ven Te Chow, 1956), Any high streamflow event which overtaxes the natural or artificial banks of a stream (Rostvolt *et al.*, 1963), or his own definition: a body of water which overflows land which is not normally submerged (Ward, 1978).

> "Even today it is not clear what makes a flood different to other events" (Beven and Carling, 1989).

The causes of floods are predominantly climatological (Ward, 1978), from rainfall, snowmelt, icemelt or a combination of the three. Partially climatological factors may also influence flooding, esturine environments being influenced by streamflow and tidal characteristics, or coastal storm surges. Other events such as earthquakes, landslides and dam failures may also cause floods.

2.2 Floods events in drylands

2.2.1 Magnitude and frequency

Wolman and Miller's (1960) investigation into relative importance of magnitude and frequency of events was of course climatically dependant (Graf, 1988). There has been substantial support for the notion that it is the higher magnitude, lower frequency events which do the most geomorphic work in drylands (Graf, 1988; Baker, 1977 in Texas; Abrahams, 1994; Gupta, 1983); whereas the higher frequency lower magnitude events are themselves controlled by the forms, working only to "embroider" them (Graf, 1988). This fact leads to a disequilibrium between form and process in dryland rivers (Graf, 1983, Cooke *et al.*, 1993). These rivers are thought to be different as a result of sediment transport. Neff (1967 in Graf, 1988) showed that dryland rivers transport as much as 60% of their sediment budget in events exceeding a return period of 10 years, in equivalent events in perennial rivers only 10% is transported. Thus, high magnitude flood events do play an important role in arid landscapes and certainly deserve further attention by hydrologists and geomorphologists.

2.2.2 Floods in Ephemeral rivers

Schick (in Baker *et al.*, 1988) postulated on whether flows in hyperarid regions are significantly different to those in wetter areas or whether they are similar in process though different in degree; Abrahams (1994) saw the difference between desert and perennial streams to consist of more than just magnitude and frequency variability. Indeed, the differing role of vegetation and infiltration rate and the dry and wet seasons all contribute to observed difference Magnitude and duration of floods are controlled by a specific set of climatological and surface factors in Dryand areas (Graf, 1988) and these combine to give flood events of a different character. A brief typology is shown in table 2.2a.

Type of flood	**Typical Duration**	**Climatological cause**	**Other**
Flash	Minute-Hours	Thunderstorm convection cell	Basins less than 100 km^2
Single Peak	Hours to Days	Tropical storm, Frontal precipitation	Basins of 1000s km^2
Multiple peak	Hours to Weeks	Tropical storm, multiple precipitation events	Wide ranges of basin
Seasonal	Days to Weeks	Tropical storm, frontal. Influence of tributary contributions to main stem	Wide ranges of basin

Table 2.2a. Generalised typology of dryland flood events, complied from Graf (1988),

2.3 Flooding in the Namib

As described in 1.3.4, the position of the Namib, approximately 23 degrees south, on the tropic of Capricorn, and on the western side of a continent next to the cold Benguela current, conspire to give a climate of low, highly variable rainfall and high evaporation. Evaporation can be up to six times that of rainfall in a given area (Stols, c. 1994 in Seely, 1989). Drought conditions are therefore normal in the Namib, as are floods, perhaps a little incongruously.

Perennial rivers only flow at the northern and southern boarders of the Namib, other than when they are supplied by small permanent springs. The westward flowing rivers of the Namib are predominantly ephemeral, only flowing in response to seasonal rains. Flow events usually occur during the wet season of October to May, when heavy convectional rains are able to penetrate the area. These heavy downpours regularly exceed the low infiltration capacity of the poor, arid soils, creating pools which converge and eventually into the main channel (see fig. 2.4a) for an example of a low flow on an ephemeral river. Higher magnitude events are thought to be connected to ENSO.

Flood flows in the Namib are vital for the survival of plants, wildlife, people, agriculture and towns of the area. Hence a better understanding of the magnitude and frequency of these floods has much relevance for planning and conservation. For example the new extraction schemes have stimulated concern over the future for water supply, Donkersan Dam on Kuiseb SWA joint venture consultants 1993 in Seely. High magnitude flood events help to recharge the aquifers which supply all these

PHOTOGRAPH 2.4a KUISEB IN FLOOD, DRIFTWOOD BEING TRANSPORTED (F.E)

needs. Floods here can also be a danger, for instance the floods of 1934 on the Kuiseb devastated the town of Walvis bay (see fig. 1.3b). Fortuitously, flood protection measures averted another potential disaster in 1963.

CHAPTER 3: METHODOLOGY:

3.1 Flood Timeline

Before fieldwork began a flood timeline was created (see table 3.1a), in order to understand the origin of deposits in the field. This timeline was compiled from a number of data sources; including historical data from Stengel's unpublished paper "Das Abkommen des Kuiseb und Swakop fur die Zeit von 1898 - 1938" and his published 1964 paper "Die Rivere der Namib und Ihr zulauf zum Atlantik: Teil 1, Kuiseb und Swakop". Information was also taken from Seely *et al.* (1980) in their paper on perennial vegetation of the Kuiseb and from more recent unpublished data collected from the Kuiseb weir and environs by Ministry of Wildlife and Tourism officials (Berry, 1995). Heyns (1990) gave a more general overview of flooding in the Namib; whilst Koch (1963) and Marker (1977) more detailed accounts of a specific flood on the Kuiseb. The only data common to most sources were on flood duration of flood. This allowed historical, anecdotal and scientific data to be combined for the records kept for the period 1837 to 1995. From this an idea of the size and frequency events was be gained.

Date	Total days	Comments	Date	Total days	Comments
1830		Full flood[6]	1968-9	1 day[3, 4]	
1837		Reaches Atlantic[1]	1969-70	34 days[3, 4]	
1848		Reaches Atlantic[1]	1970-1	34 days[3,4]	
1849		Reaches Atlantic[1]	1971-2	43 days[3, 4]	
1852		Reaches Atlantic[1]	1972-3	15 days[3, 4]	
1864		Reaches Atlantic[1]	1973-4	102 days[3,4]	To salt marsh[6]
1880		Reaches Atlantic[1]	1974-5	10 days[3, 4]	
1881		Reaches Atlantic[1]	1975-6	61 days[3, 4]	
1885		Reaches Atlantic[1]	1976-7	68 days[3, 4]	554% av an rainfall[8]
1893		Reaches Atlantic[1]	1977-8	77 days[3, 4]	Reaches saltmarsh
1903-4		Reaches Atlantic[2,5]	1978-9	8 days[3, 4]	
1916		Breaks through wall	1978-9	No flow[3]	
1917		Reaches Atlantic[1]	1979-80	No flow[3]	
1923		Reaches Atlantic[1,2]	1980-1	No flow[3]	
1931		Reaches Atlantic[1]	1981-2		
1934		Reaches Atlantic[1]	1982-3		
1942		Reaches Atlantic[1]	1983-4		
1950		Reaches Walvis Bay[1]	1984-5		
1951		Reaches Mile 39[1]	1985-6	No flow[3]	
1953		Reaches Mile 3[1]	1986-7	16 days[7]	
1956	6 days[1]	Past Rooibank[1]	1987-8	9 days[7]	
1957		To Mile 16[1]	1988-9	22 days[7]	
1961		To Mile 13[1]	1989-90	8 days[7]	
1962-3	68 days[3, 4]	Reaches Atlantic[1]	1990-1	18 days[7]	
1963-4	26 days[3, 4]		1991-2	8 days[7]	
1964-5	18 days[3, 4]		1992-3	4 days[7]	
1965-6	22 days[3, 4.]		1993-4	26 days[7]	
1966-7	11 days[3, 4]		1994-5	8 days[7]	
1967-8	18 days[3, 4]		1995-	15 days[7]	

Table 3.1a Flood events on the Kuiseb

[1] Stengel()
[2] Stengel (unpub.)
[3] Seely and Ward in Breen and ward ()
[4] Seely *et al.*
[5] Koch
[6] Have
[7] Berry
[8] Marker (1977)

3.2 Fieldwork:

3.2.1 Transects.

To identify the location of wood deposits, a transect method was selected. It provided the most effective and objective way of sampling deposition along the river. The reach was covered at first on foot (Transects 1 to 13)(fig 1.3e), and thereafter by three wheeled motorcycle, due to larger distances and weight of equipment.

To ensure that the whole reach could be surveyed within the five weeks allotted and that sufficient detail of coverage was achieved, fifty four transects were taken at three hundred metre intervals (fig. 1.3e). Transects were located by pacing from one to another, a quick method accurate and appropriate enough for the scale involved, if checked regularly. A 100m control was used, measured with a 50m PVC tape, and repeated the practice at regular intervals to ensure precision. Later landmarks were used to locate the transects on colour satellite photographs (1: 50 000, Namib) and topographical maps (SWA/Namibia 1:50 000, sheets 2314BD (1980 second edition), 2314 DB (1979 first edition) and 2315CA (1980 second edition).

Each transect extended 300m either side of the river channel, from an estimated central point, as the reported extent of deposition was 200m. Distances were measured by a combination of levelling to the first 100m, and pacing for the remainder. The precision of this was checked independently. Transect lengths were occasionally limited by impenetrable vegetation on either side, or particularly high dunes on the south side.

Originally three transects per site were planned, at 45^0 90^0 and 135^0 to the channel. However, given time constraints, transects were taken at 90^0 to the channel only, following Williams and Costa's recommendation for post flood surveys (in Barker *et al.*, 1988). The orientation was established by a hand bearing compass and a landmark in middle distance was located as a reference datum.

3.2.2 Driftwood data collected.

Within each transect six variables relating to driftwood deposition were measured.

(i.) Location of the deposit, to the nearest levelling measurement or ten metres of pacing, from which a driftwood map could be composed.

(ii.) The size of the deposit in two dimensions, width and length (following Williams and Costa) using a 20m steel tape measure.

(iii.) Typical dimensions of individual logs within the deposit, diameter and length, using the steel tape and a small 10 cm ruler. An arbitrary cut-off point was decided upon, that wood below 4 cm diameter would not be surveyed, this was more likely to have been brought down in a low magnitude event (see photographs 2.4a and 3.2a).

(iv.) Typical spacing between individual logs or accumulations was also taken, using 50m PVC tape measure, steel tape or rule as appropriate.

(v.) Orientation of the deposit was recorded, by hand bearing compass, in order to gain a greater understanding of the flow direction during flooding.

(vi.)The estimated relative age of the wood. As the rate of decay in deserts is slow, this was difficult, and it could not be measured from soil

Photograph 3.2a Small driftwood with typical diamteters of 0.3-2cm

Photograph 3.2b Old partially buried deposit

formation or vegetation colonisation. Instead degree of cracking, as measured by rule, loss of roundness in shape and the integrity of the wood was noted (i.e. degree of crumbling). Partially buried deposits were considered to be older (see photograph 3.2b).

The last criterion was difficult to estimate, yet after a number of transects it began to appear that there were four two five general dates of wood and therefore different locations could be linked.

Appendix 3. shows an example of a data sheet used in the field, listing these factors.

3.2.3. Qualitative Data

Data was also collected on channel characteristics and deposits by sketches, photographs and by a paced longitudinal transect.

3.3 Channel widenings

Measurement to a particular flood stage is a recognised way of recording width (Richards, 1982). In this case it would have been appropriate to use typical flood flow height as the datum. Unfortunately this data was unavailable for the reach, and therefore the conventional methods of measuring bankful width were employed (Knighton 1984, Richards 1982). To compensate for this channel width was also measured from maps and satellite photographs, which tended to give a higher value, and the "floodplain" was also surveyed to 100m either side of the channel for each transect, to give a visual representation of whether there were widenings of the channel/valley at higher stages of water.

3.3.1. Field Data

Widths exceeding 2-3m may not be measured by tape (Richards 1982). It was therefore taken whilst levelling. Bankful indicators used were:

(i.)Marked changes in slope perpendicular to the channel (following Kilpatrick and Barnes 1964 in Goudie 1989) (see photograph 3.3a).
(ii.)Sediment change (Nonally 1967 in Goudie 1989).
(iii.)Marks in sediment parallel to flow and (Williams and Costa 1988).
(iv.)Vegetation change (Williams and Costa 1988)
(v.)Debris in vegetation (Dunkersley 1992)

The sediment and vegetation recordings on the results sheet (Appendix 3) enabled the bankful level to be estimated in data interpretation.

An Abney level would have been ideal for levelling as it requires only one observer (Cox in Goudie, 1989), however only a Wild NK 01 dumpy level was available at the research station. A spare tripod was utilised to hold the staff (photograph 3.5b), attempts were made to keep this vertical, and when tested it produced comparable results to that of a person holding it. Although the modern practice is to level sections of 5m or less (Cox in Goudie, 1989), the older practice of measuring to breaks in slope was used, as it was simpler for one operator. It was also thought that this would show small height changes against the vast horizontal extent more clearly and

Photograph 3.3a Bankfull mark in sediment

Photograph 3.3b Dumpy level and staff used for the survey

therefore highlight higher flow widenings and constrictions. Surveying took place at 90^0 to channel flow (following Williams and Costa 1988).

Minor problems with the equipment were encountered, legs becoming detached from tripods, the staff requiring repainting of calibrations, sand becoming lodged in the level and heat distortion of levelling bubbles all lead to compromises in accuracy, which must be taken into consideration when interpreting results.

3.3.2. Secondary Data

Richards (in Goudie, 1989) shows how aerial photographs and topographical maps can be used to measure channel width of wide channels.

> "Channel width may be inferred from vegetation or sediment patterns obviating the need for field surveys and introducing aerial photographs as a potential data source"

Maps (listed above) obviously had channel limits designated by the cartographer, but for the aerial photographs vegetation and sediment change was used as a proxy indicator. As Richards later pointed out this is only useful as a supplement to morphological survey.

3.4 Channel Constrictions by bedrock

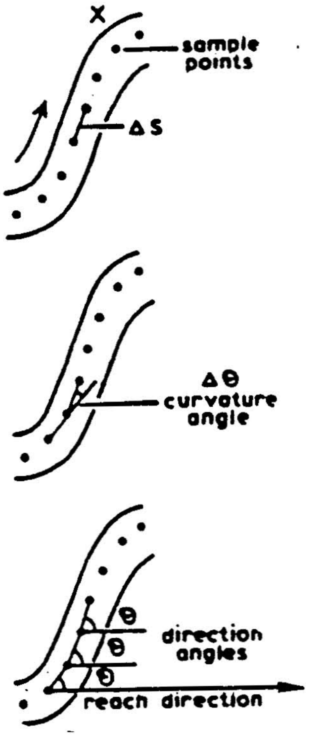
The method here was the same as above, with the addition of noting, sketching and photographing obvious bedrock outcrops at each transect.

3.5 Channel bends

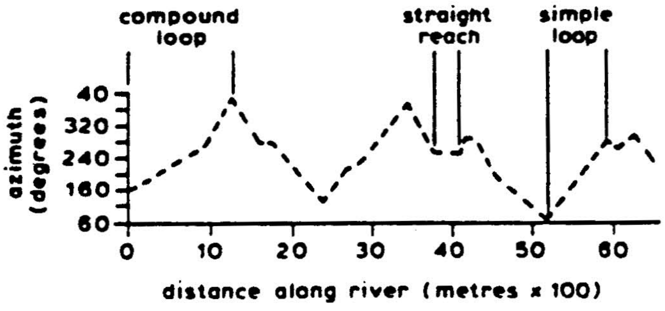
The conventional measure of river pattern is that of braiding, meandering or straight description (Knighton 1984). This was not appropriate in this case as statistics on individual bends were required. Traditional individual bend measures include measuring axial and path wavelength, radius of curvature and amplitude (Knighton 1984). There can be severe problems with operational definition of these measures (Richards, 1982), and this method has been superseded in many places by the newer one dimensional series analysis. This method is objective and flexible (Knighton, 1984), treating the stream trace as a spatial series of direction or direction change in terms of distance along the path (fig. 3.5a). It is especially useful in this case as it can be used to distinguish between bends and straight reaches (after Brice, 1973 in Richards, 1982).

This method involved representing the channel as a series of equidistant midstream points, the centres of which may be arbitrary (Richards, 1982), and in this case were set at 100m. This length was selected as the smallest practical length to work on a 1:50 000 map. A baseline is drawn oriented NW (315^0), the azimuth or direction of the section away from the baseline was then measured in degrees, and plotted against path distance. Interpretation was after Brice (1973, in Richards, 1982) who used the graph to distinguish between meandering and straight reaches (fig. 3.5a). Additional data was taken in the field as to obvious bends, channel direction and their relation to deposits.

Fig. 3.5a Channel bend series analysis, after Brice (1983) in Richards (1982)



(a) Measuring direction angles (azimuth) between sections and baseline



(b) Plotted results and key to interpretation

3.6 Partial Damming by dunes

Dunes no longer dam the river, so areas of possible blocking had to be inferred from the field and existing secondary data.

3.6.1 Field Data

An obvious sign that a dune had dammed the river would be that red-brown (Goudie, 1989) dune sand was found on the northern gravel bank. Therefore substrate material was noted throughout the transects (Appendix 3).

Proximate dunes would be more likely to have dammed the channel recently than those further away. Distance of dunes away from the channel was, therefore, taken in the field, by pacing. This provided a more sensitive measure of dune condition than from a map, where the only indication of dune edge would be a contour.

3.6.2 Secondary data

Maps, Aerial photographs and satellite photographs were used to draw a basemap of dune position with respect to the transect. Data on direction and speed of movement of relevant dunes from Lancaster (in Huntley, 1987) was overlaid on this basemap.

CHAPTER 4: RESULTS

4.1 Driftwood distribution results

4.1.1 Data interpretation

The initial stages of data interpretation involved the construction of profiles from raw transect data, to show distance from channel against number of wood pieces logged. Distance measured between readings was calculated from surveying data, using upper minus lower stadia reading, multiplied by 100. This was combined with pacing results to provide x-axis data. Profiles show channel at 0m from transect and dune side as negative. Non-uniform distances between readings unfortunately precluded the use of histograms for the profiles, instead scattergrams were drawn.

High magnitude flood deposits were to be investigated, this implies wood of a larger size than the 4cm diameter cut-off point used in the field. There being no hydrological or geomorphological definition of the critical size of wood carried and deposited in such a flood, or even a biological distinction between twig, branch and trunk, an arbitrary level, above the upper quartile of 22 cm diameter, was chosen. Transects were also made of wood which fell into this category.

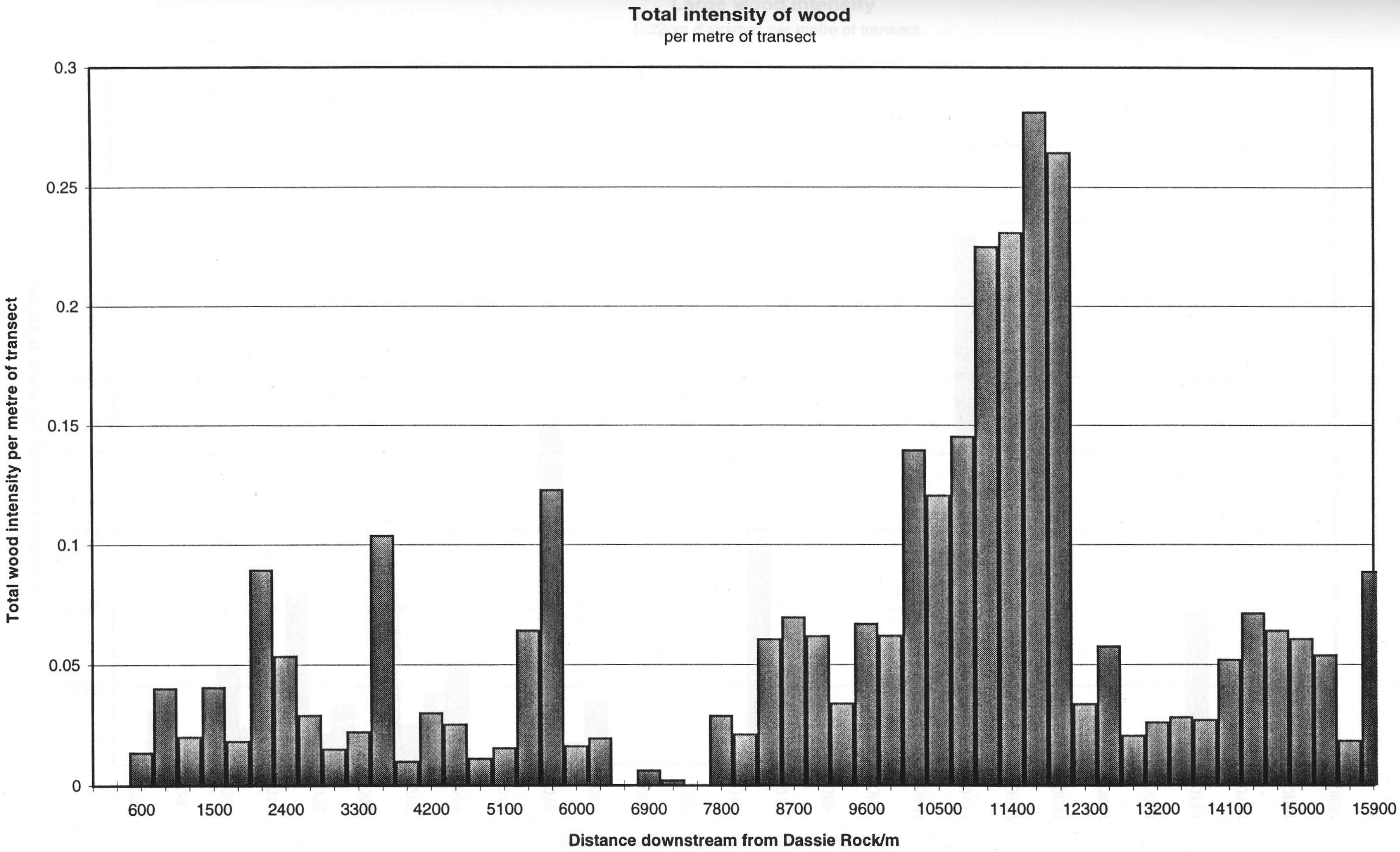
These results mean little as individual observations, an overall view of the channel was necessary in order to understand the three dimensional depositional environment and the patterns of driftwood deposition. Unfortunately software to stack transects successively was unavailable, therefore a mapping program "SURFER" was employed. For this data manipulation was necessary. Firstly wood data was standardised and intensity calculated per meter of transect for both total and "large" wood (above 22 cm) (see histograms 4.1a and b for longitudinal data). Data from all transects were then amassed and gridded by the program to create a three dimensional surface. Kridging was the interpolation method selected, the best general technique for most kinds of data (Golden Software inc., 1994). Results were converted into a contour plot see fig. 4.1c for total data and 4.2d for large wood. Plots show intensity of deposition away from a standard, straight channel at 0m, at a horizontal exaggeration of 400%.

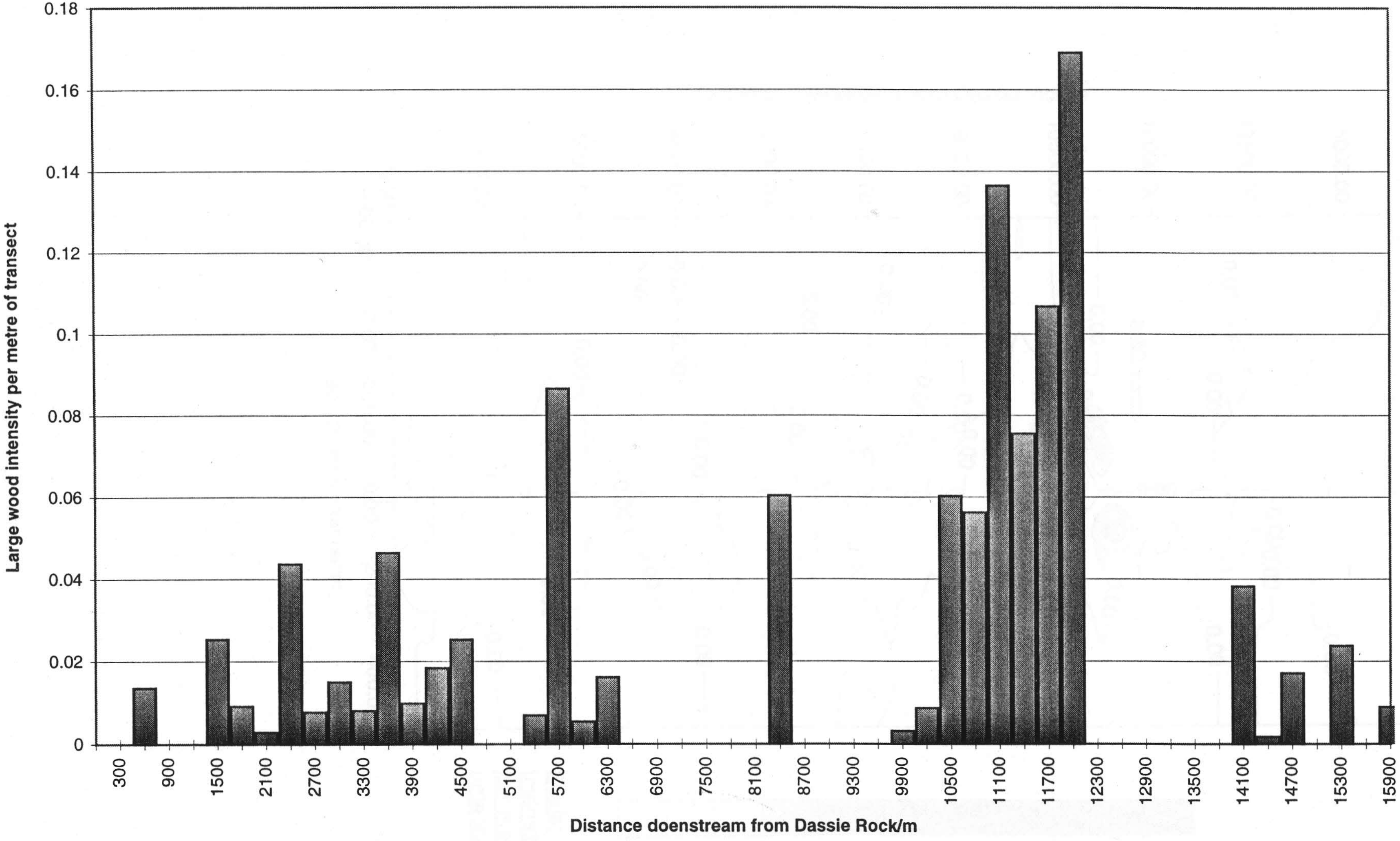
These data were then augmented by field sketches (Appendix 2) and photographs 4.1a, b, c d and e).

4.1.2 Results

Patterns of deposition perpendicular to the channel may be seen in figure 4.1c and 4.1d. These show higher intensities, peaking at 4.5 pieces/m, and greater spatial extent of total wood on the dune side. Large wood mirrors this pattern. Bands of lower deposition, at below 0.5 pieces/m can be seen between 3 000 and 3 600m, 6 600 and 7 800m, 11 100 and 13 200m, which taper with distance away from channel.

Longitudinally deposition is divided into three zones. Between 0 and 8 400m downstream total and large wood intensities are low, but include several marked peaks which can be more clearly seen on 4.1a and b. Other low intensity areas occur between 12 000 and 15 900m at around 0.4 pieces/m for total wood (see fig. 4.1a). Maximum deposition lies between 8 400 and 12 000m, with five distinct lobes of high


Total intensity of wood
per metre of transect
Total wood intensity per metre of transect
0.3
0.25
0.2
0.15
0.1
0.05
0
600
1500
2400
3300
4200
5100
6000
6900
7800
8700
9600
10500
11400
12300
13200
14100
15000
15900
Distance downstream from Dassie Rock/m

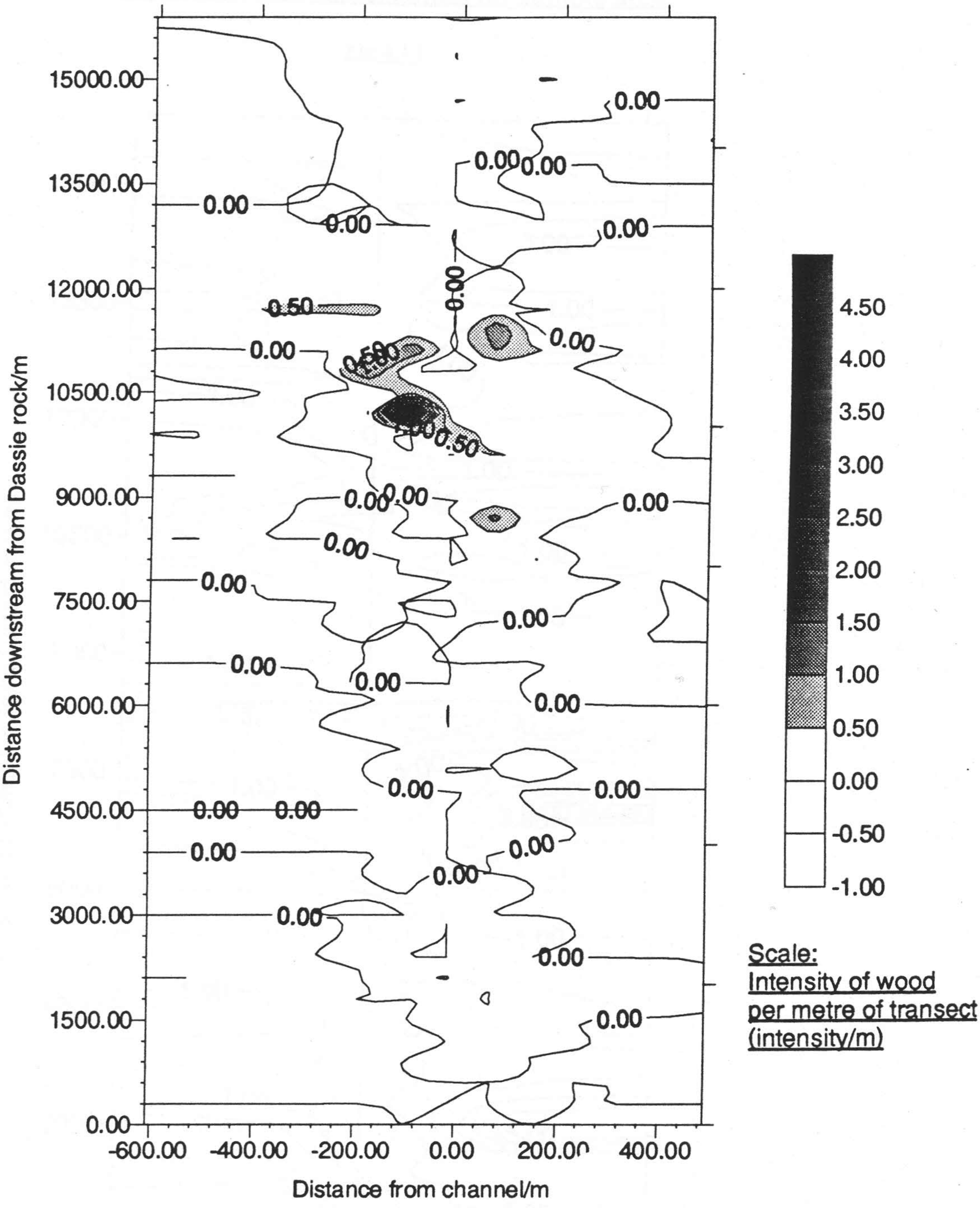


Large wood intensity

(>22cm diameter) per metre of transect

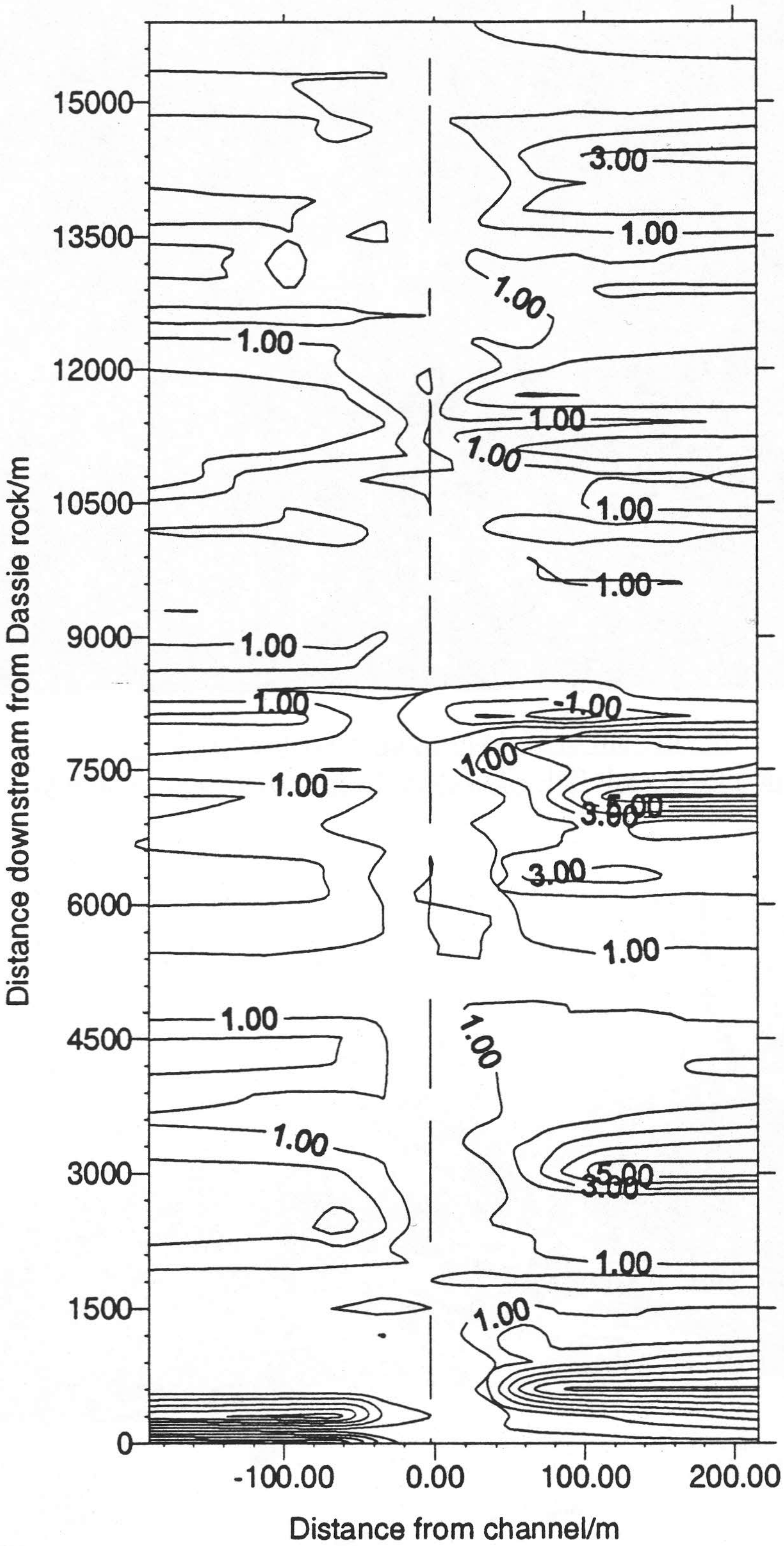
Fig. 4.1c

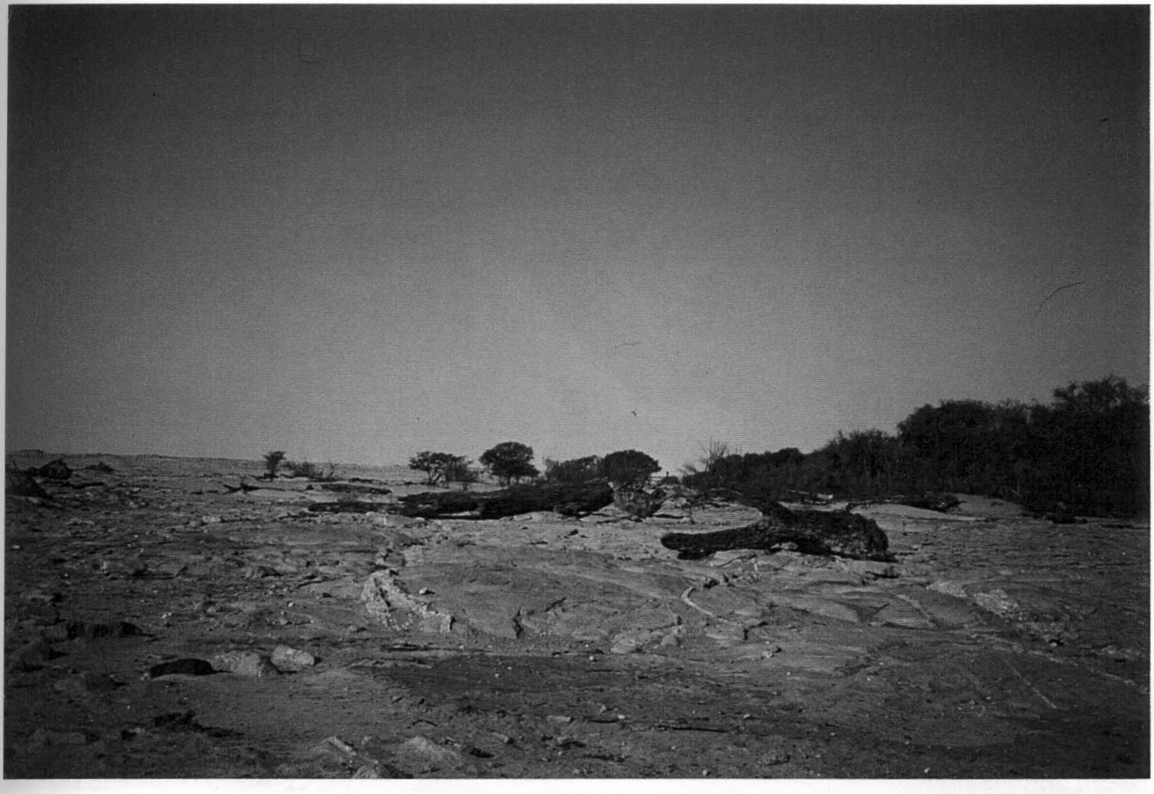
Contour plot to show total distribution of wood over sample area



Contour plot to show height above channel datum for sample area

Fig 4.1d





Photograph 4.1a Soutriviere deposit close to the village
To the right hand side the riverine forest, to the left the gravel plains

Photograph 4.1b Compact accumulation at transect 35, High intensity of large logs caught behind bedrock outcrop

Photograph 4.1c Weir accumulation, deposited 8m from the channel to the dune side. Photograph shows large diameter (staff is 3.5m long)

Photograph 4.1d Large stacked accumulation to the gravel side (staff is 3.5m long)

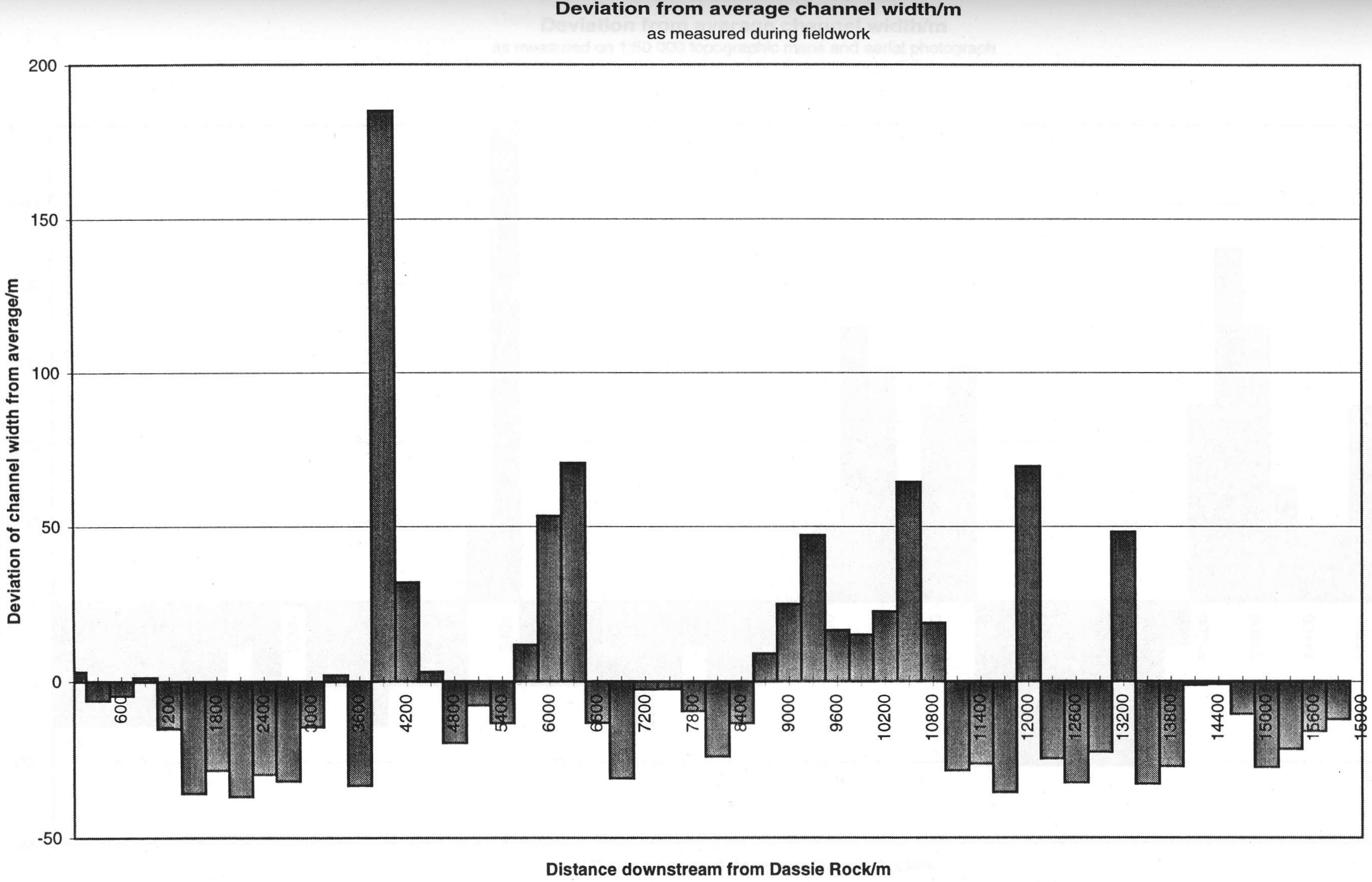
intensity in the total wood (fig. 4.1c), and three in the large wood (fig. 4.1d). Figures 4.1a and b show medium intensity for total wood (just over 0.05 pieces per meter) and low intensity for large wood between 8 400 and 9 600. This will henceforth be called the "Soutriviere to Weir site". Photograph 4.1a gives an impression of this deposit in the field. Very high deposition for both total and large wood lies mainly in the 9 900 and 12 000 band, corresponding to transects 14 to 20, which will be called the "Weir site" fig. 1.2 shows the position of the weir with respect to the transects. Sketch map 4.1e and photographs at 4.1c and d respectively give the overall impression of this site, and photographs 4.1g and h depict the large diameter and number of logs brought down m in a high magnitude flood on this river. A high deposition area was found at transect 35, due to interpolation methods this does not appear clearly on the contour plot, fig. 4.1f shows the transect for the area and 4.1b the close packing of the logs.

4.2 Channel widenings

4.2.1 Data Interpretation

Widenings could be isolated by plotting field channel width against distance upstream as deviation from the average see fig. 4.2a that above the datum line is wider than average. This was repeated for combined data gleaned from maps and aerial photographs see fig. 4.2b, figure 4.2c shows the two indices combined.

By calculating a running series of distances and heights from surveying data, sets of slope profiles could be drawn. The data set was then compiled and gridded in the manner described under 4.1.1 to give a three dimensional contour plot of height

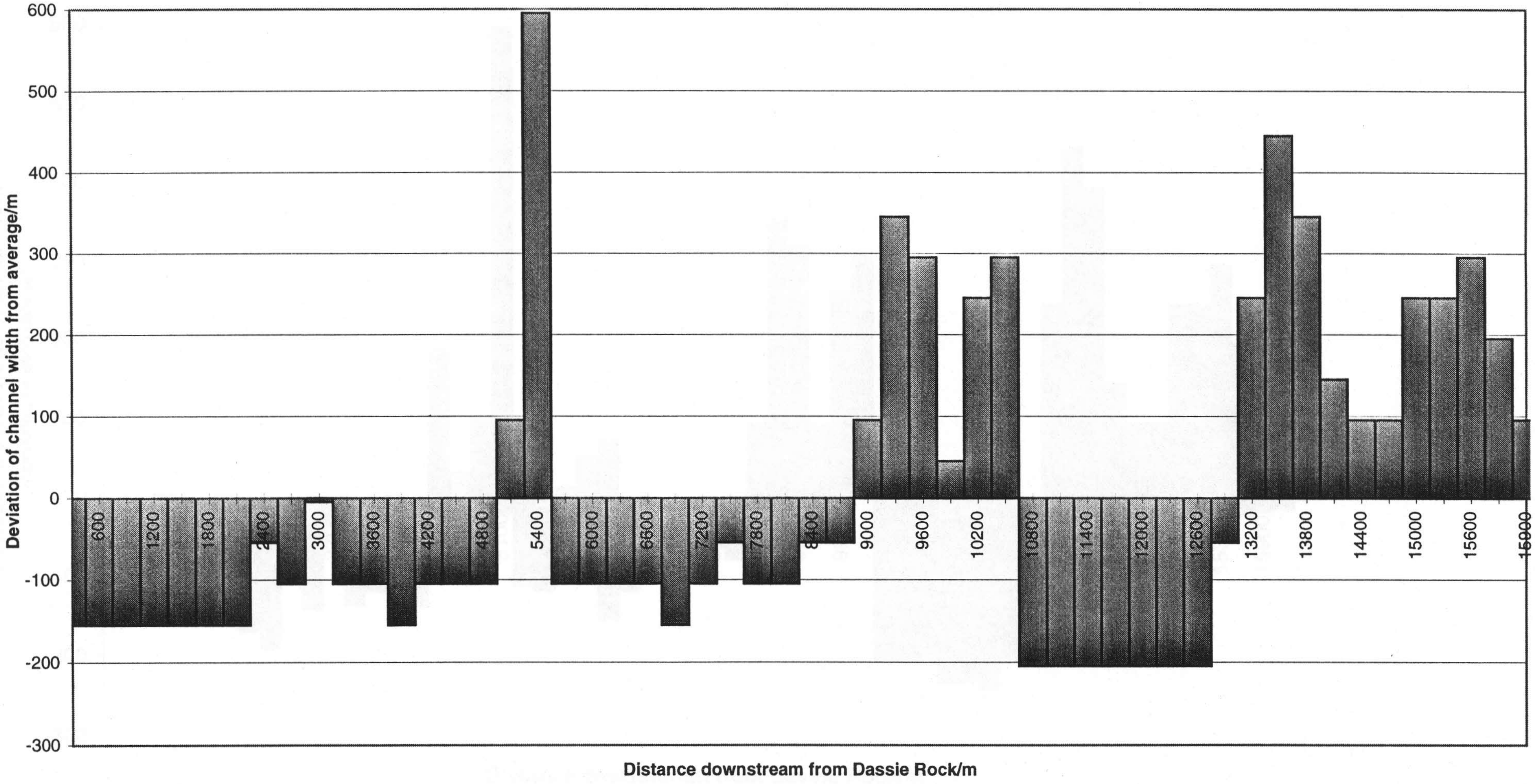


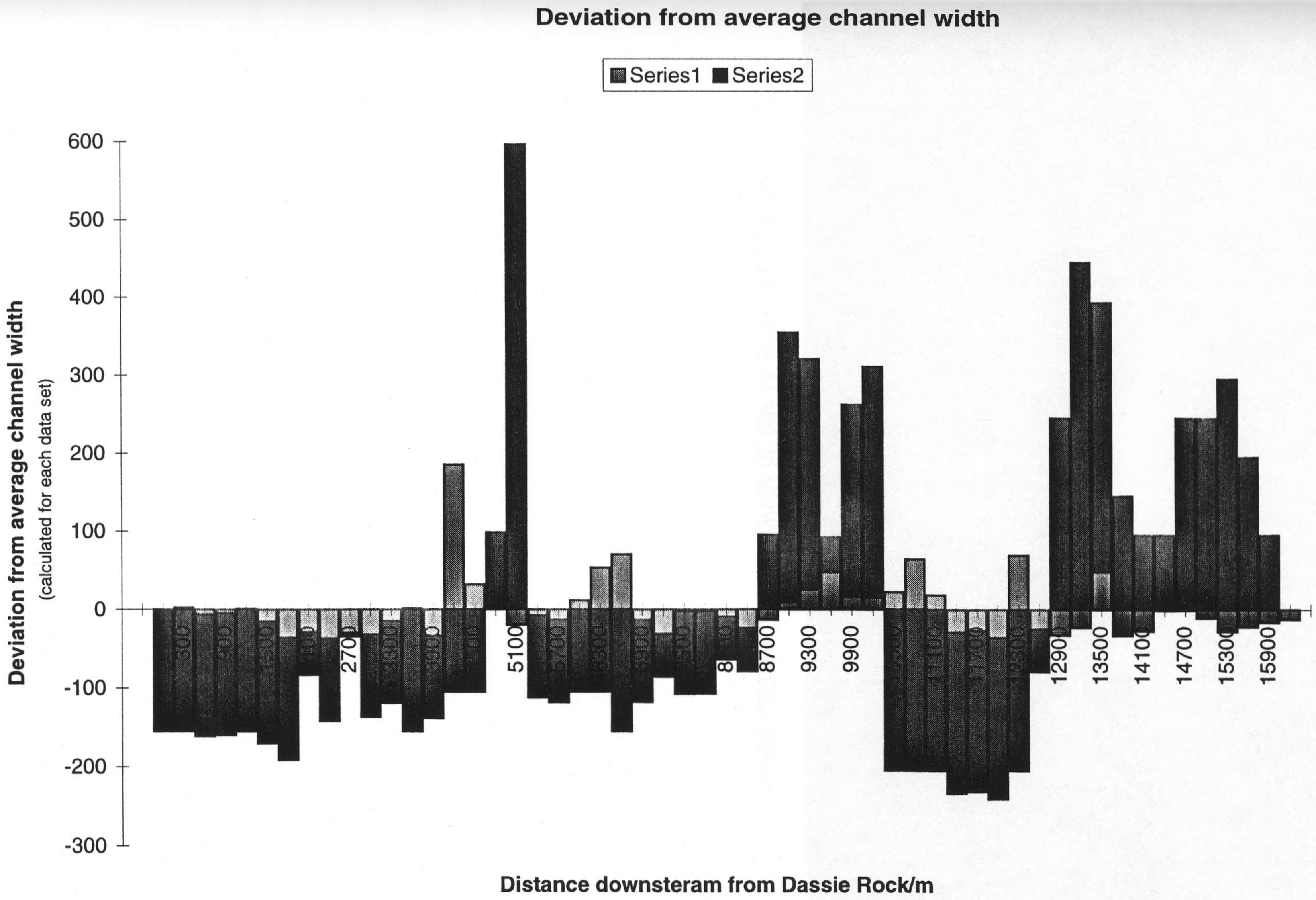
Deviation from average channel width/m

as measured during fieldwork

Deviation from average channel width/m

as measured on 1:50 000 topographic maps and aerial photograph




Deviation from average channel width
Series1
Series2
600
500
400
300
200
100
0
-100
-200
-300
Deviation from average channel width
(calculated for each data set)
2700
5100
8700
9300
9900
12900
13500
14100
14700
15300
15900
Distance downsteram from Dassie Rock/m

Photograph 4.2a Transects 37 and 38 showing wide, straight, channel

against channel bed datum (Fig 4.2d). From this widenings of the channel at any flood stage could be identified.

4.2.2 Results

Field data (fig. 4.2a) shows isolated channel widenings to be at 12 000m and 13 200 and small widenings at 0, 900, 3300 and 4500m downstream. There are three zones of channel widenings, between 3900 and 4500m, 5800 and 6300m, (see photograph 4.2a) and between 8700 and 10 800m. The larger channel, as identified by map and aerial photograph data (fig. 4.2b), also shows three areas of widening, 5100 to 5400m, 9 000 to 10 500m and 13 200m. Correlation between the two indices is reasonable, (fig. 4.2c) general patterns of widening are reinforced, with the exception of conflicting results between 5 700 and 6 600 and 12 900 and 15 900m.

The three dimensional representation of the channel, fig. 4.2d shows obvious widenings between 3 300 and 3 900, 4 500 and 6 000, 9 000 and 10 500, results which broadly correlate with other widening indices, and especially closely with map data.

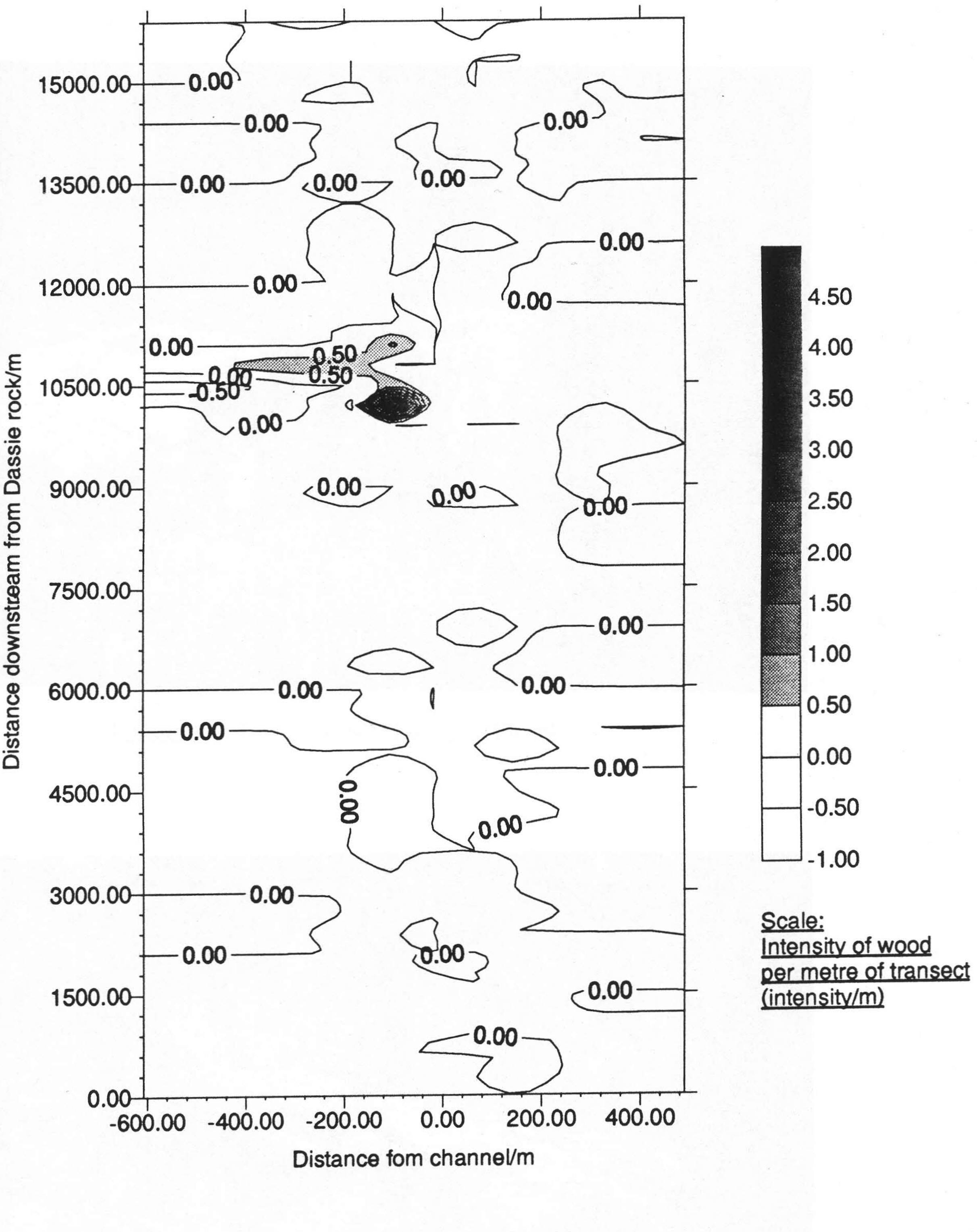
4.3 Channel constrictions

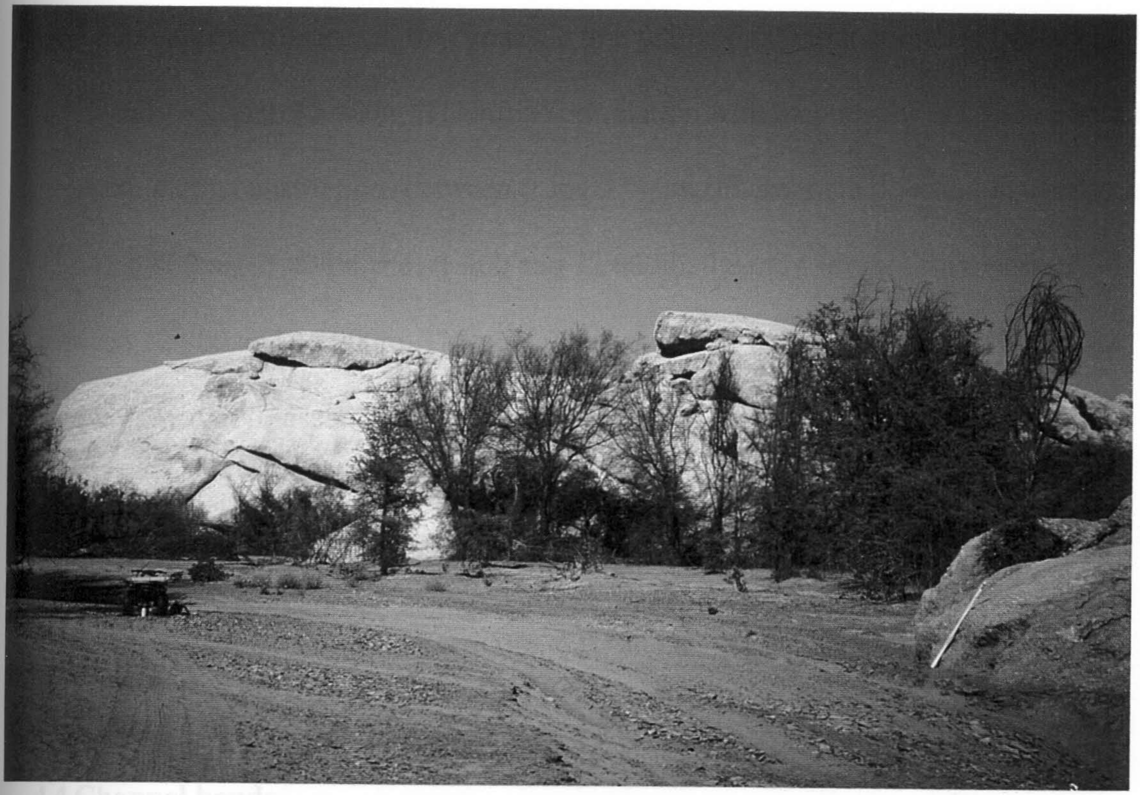
4.3.1 Data interpretation

Method was identical to that of channel widenings, excepting constrictions being those points on the total transect wood/m: width plots which fell below the datum line and the inclusion of data on location of bedrock constrictions.

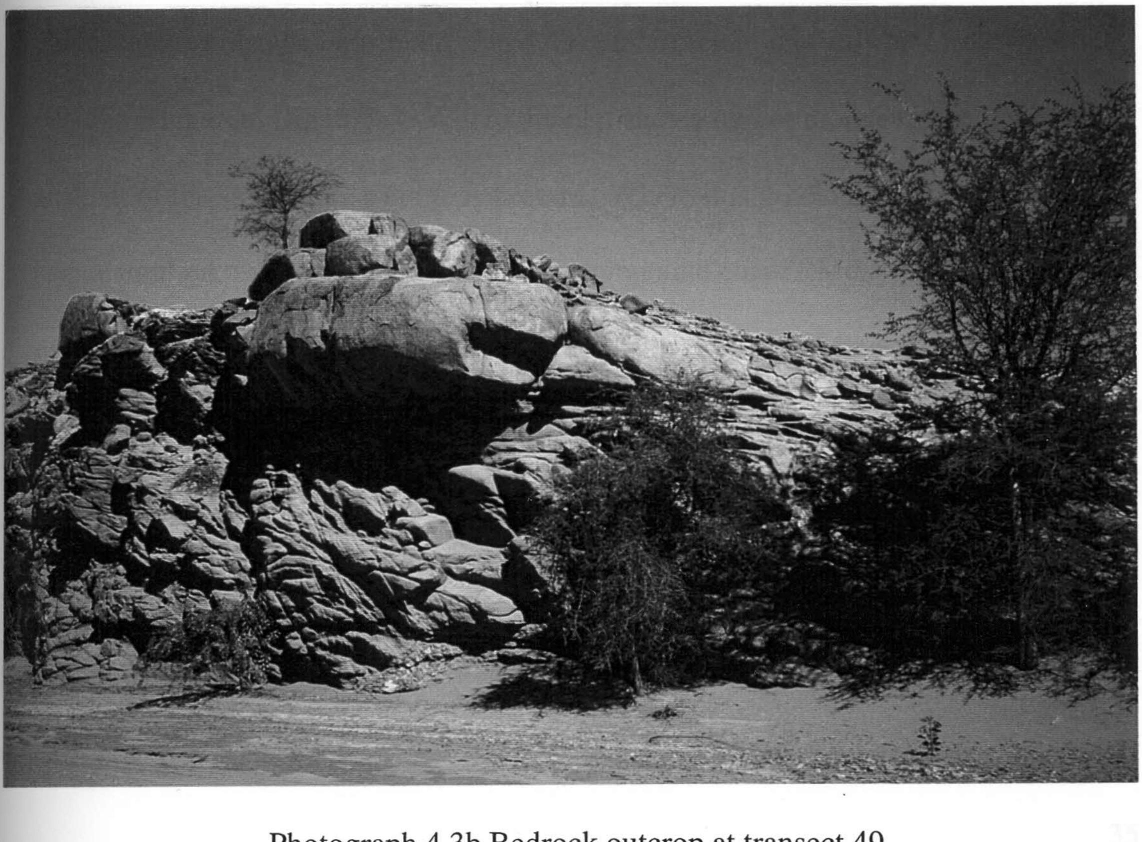
Fig 4.2d

Contour plot to show large wood distribution (>22cm diameter) over sample area





Photograph 4.3a Bedrock outcrop at transect 52



Photograph 4.3b Bedrock outcrop at transect 49

4.3.2 Results

If exceptions are made for the few isolated widenings, channel constrictions (from field data) appear to occur in four zones, 0 to 5 400m, 6 600 to 8 400m, 11 100 to 11 700m and 135 00 to 15 900m. The broad correlation with map results is a little better here (fig. 4.2c), constrictions between 0 and 3 900m (Photograph 4.3a and b, transects 43-54), 5 400 and 8 400m and 11 400 and 12 600m, the only strong disagreement between 12 900 and 15 900m. The only major evidence of bedrock constriction from fieldwork was at transect 35 and between 43 and 54.

The contour plot shows some relationship to the other indices, constrictions are between 0 and 600m, 1 800 and 4 500m, 6 00 and 8 100m and 10 500 and 12 000m.

4.4 Channel bends

4.4.1 Data interpretation

Segment azimuth, the angle between the segment direction and the baseline, was plotted against distance upstream (fig. 4.4a). Interpretation of this plot follows Brice (1973 in Richards) (fig. 3.5a). Where the plot shows two or more segments with a gradient of the same sign, a curve is present. Where this gradient is constant a simple loop is implied, where it varies it depicts a compound curve. Most importantly, straight or “non bend” reaches appear on the plot as horizontal lines (gradient 0), or where the sign of the gradient changes from one section to the next. Naturally actual data rarely return the clean results depicted in fig. 3.5a, generalisations were therefore made.

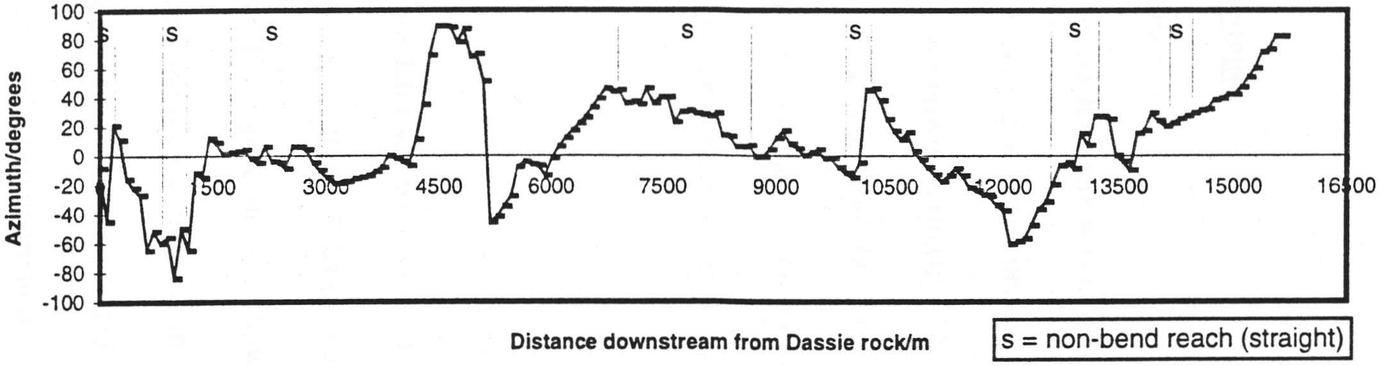

4.5a Bend analysis

Figure 4.4a shows an irregular pattern of meanders, within which there are few straight reaches. Fairly straight reaches are between 0 and 300m, 900 and 1 200m, 1 800 and 3 000m, 6 900m and 10 200m, 12 600 and 12 900m and 14 100 and 14 400m. The remaining areas are classed as either complex or simple curves on the diagram.

4.5 Partial Dune damming

4.5.1 Data Interpretation

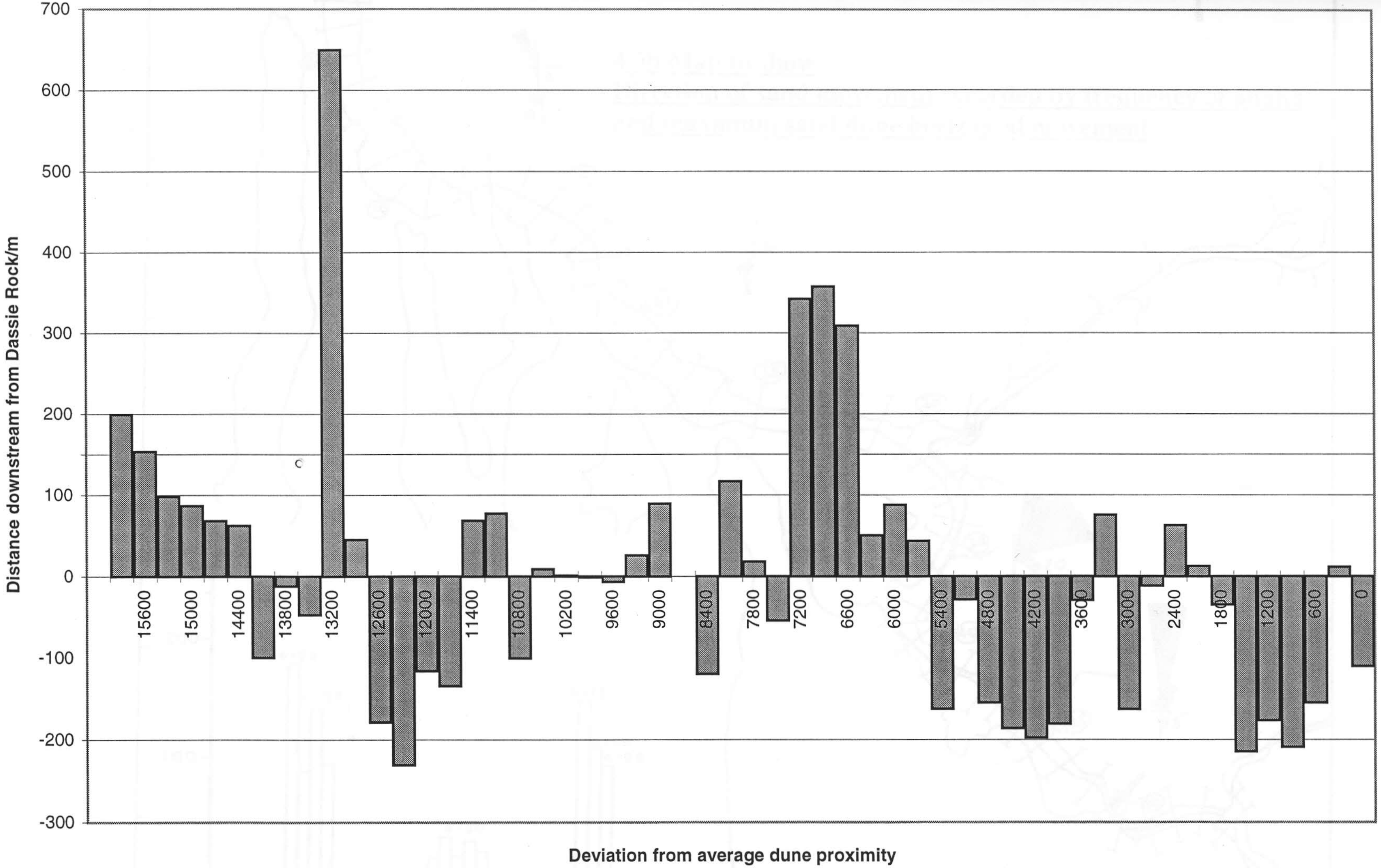
Sediment recording found that there was no obvious dune sand on the gravel plain river bank. Field results of dune proximity were plotted as deviation from an average of 251m, against distance downstream (fig. 4.5a) to show areas of particularly close dunes more clearly. A basemap from the 1:50 000 topographic maps was used to compile a composite map of dune orientation with respect to transect, speed and direction of dune of movement, and therefore risk areas of damming by dunes (fig. 4.5b) .

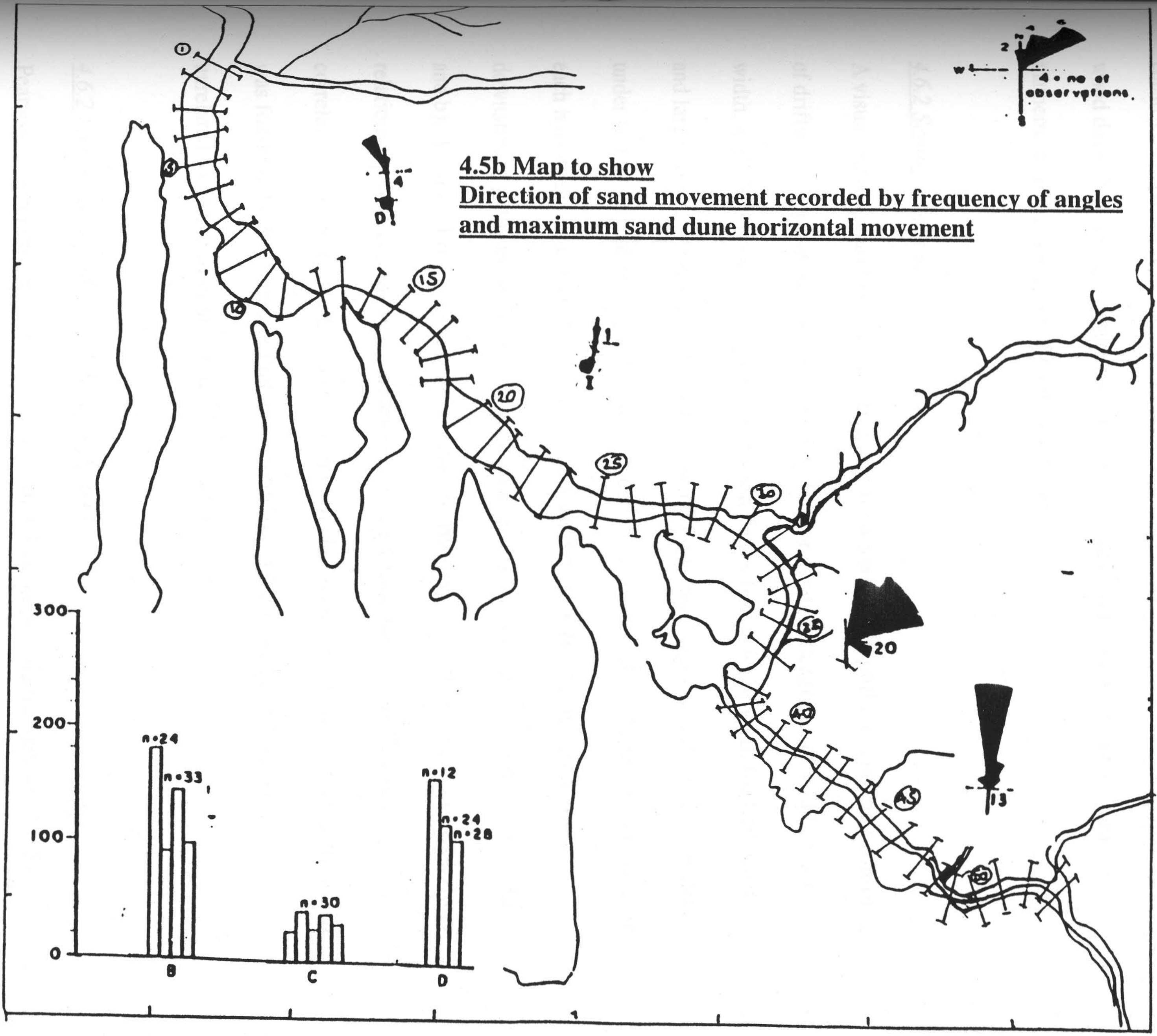
4.5.2 Results

Areas of possible dune damming would seem to be where the dunes are closer, i.e. at 0, 600 to 1 800, 2 700m to 5 400m, 7 500m, 8 400m, 10 800m, 11 700 to 12 600m and 13 500 to 14 100. The composite map shows that the areas of maximum risk where the head of the dune is close, moving in the direction of the channel at a fast velocity. The risk areas (fig. 4.5b) were found to be greatest in the vicinity of Gobabeb station dune, where maximum horizontal movement is 180 cm/yr. (Lancaster, 1987).

4.5a Dune Proximity

plotted as deviation from average





4.5b Map to show
Direction of sand movement recorded by frequency of angles and maximum sand dune horizontal movement

Histogram. Vertical scale cm/yr, each vertical bar represents one dune monitoring site.

Rose diagrams direction of sand movement recorded by frequency of angles

4.6 Causal relationships

4.6.1 Subjective assessment

Data were first looked at subjectively, comparing areas of notable channel widening, constriction, bends or dune encroachment with regions of high intensity or large wood data. No single hypothesis stood out as a reason for these deposits, more mathematical methods were therefore necessary.

4.6.2 Scattergrams and correlations

A visual representation of any relationship between each hypothesis and the position of driftwood deposition was then sought. Exploratory scattergrams of width, map width, and dune proximity against driftwood deposition were plotted, for both total and large wood. It was hoped that these would give an insight into the nature of data under test as well as the relationship between the two variables. As the major effect of each hypothesised cause of the deposition would be in influencing upstream-downstream patterns of driftwood, data was resolved to longitudinal only (Figs 4.1a and b). Figures 4.6a, b, c, d, e and f show the results. Each shows little or no obvious relationship between the two variables. To verify this statistically Pearson's correlation was performed, and is shown in the left hand corner of the scattergrams. It was found to be 95% certain that any variation in total or large driftwood was unrelated to variation in any of my hypotheses.

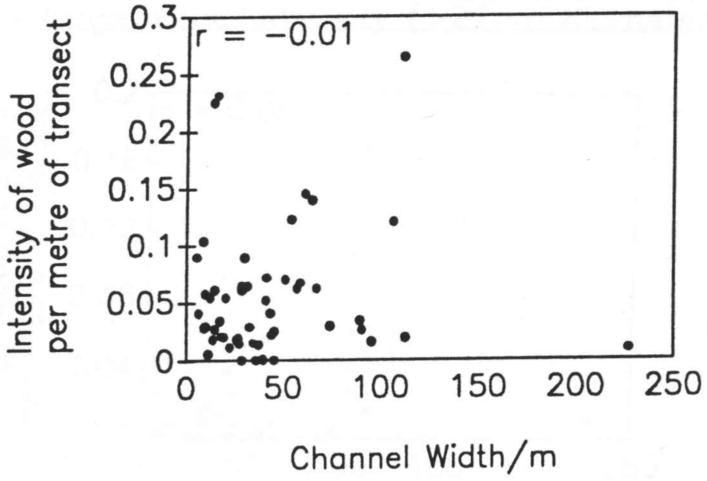
4.6.2 Spearman's rank correlation coefficient

Pearson's correlation coefficient assumes that data are parametric (Ebdon 1985). Product-moment correlation would be inappropriate if data were skewed. Box plots

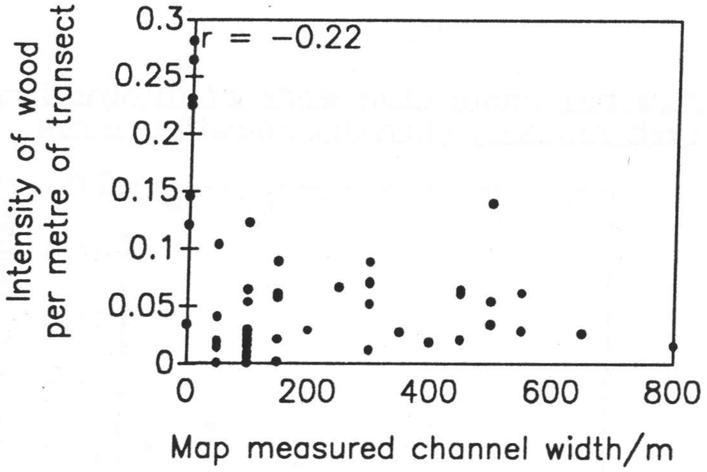
Fig 4.6 a-c

Basic scattergrams

Scattergram to show channel width against wood intensity



Scattergrams to show map channel width against intensit of wood per metre of transect



Scattergram to show dune proximity against wood intensity per metre of transect

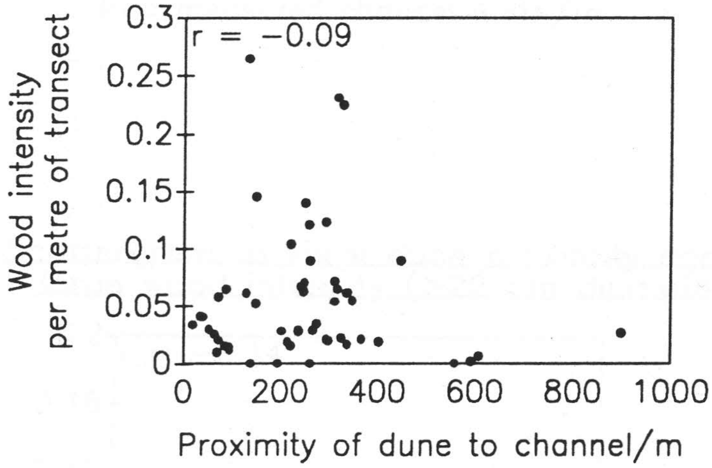
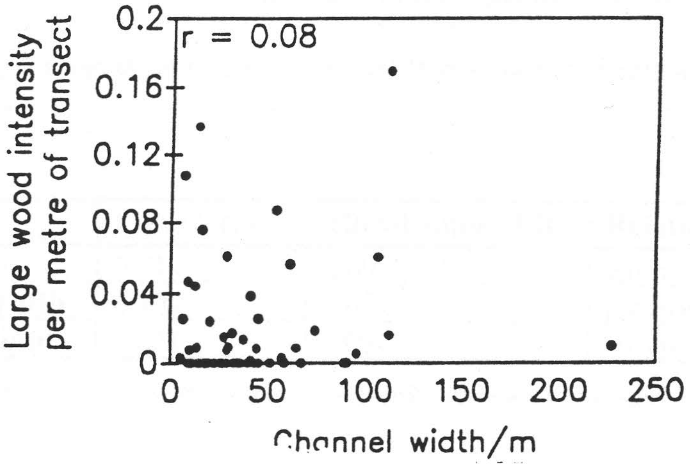


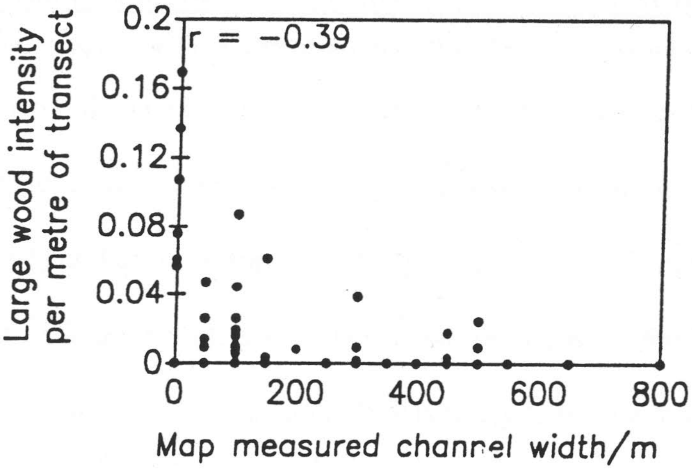
Fig 4.5 d-f

Scattergrams showing large wood (>22cm diameter)

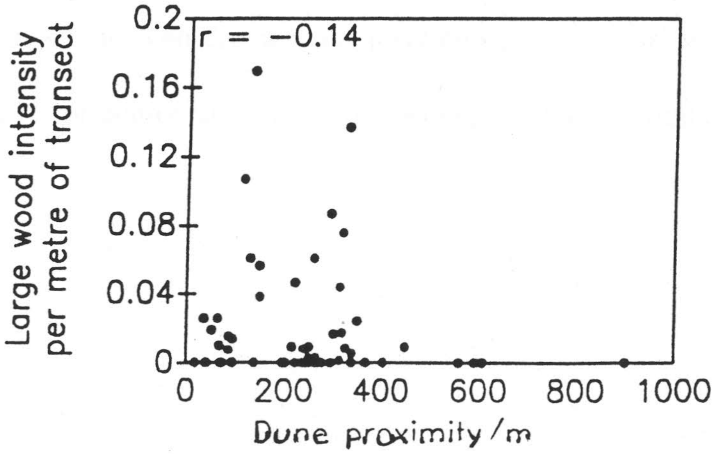
Scattergram to show channel width against large wood intensity (>22cm diameter)



Scattergram to show map measured width against large driftwood intensity (>22cm diameter)



Scattergram to show dune proximity against large wood intensity (>22 cm diameter)



were drawn to discover if data were normally distributed. These show the median and quartiles as a heavy lines and mean as a light line. They indicate positively skewed data (see figs. 4.6g and h). On the basis of this Spearman's rank correlation was carried out on ranked data, see appendix 1. for working. Table 4.6c below shows the results.

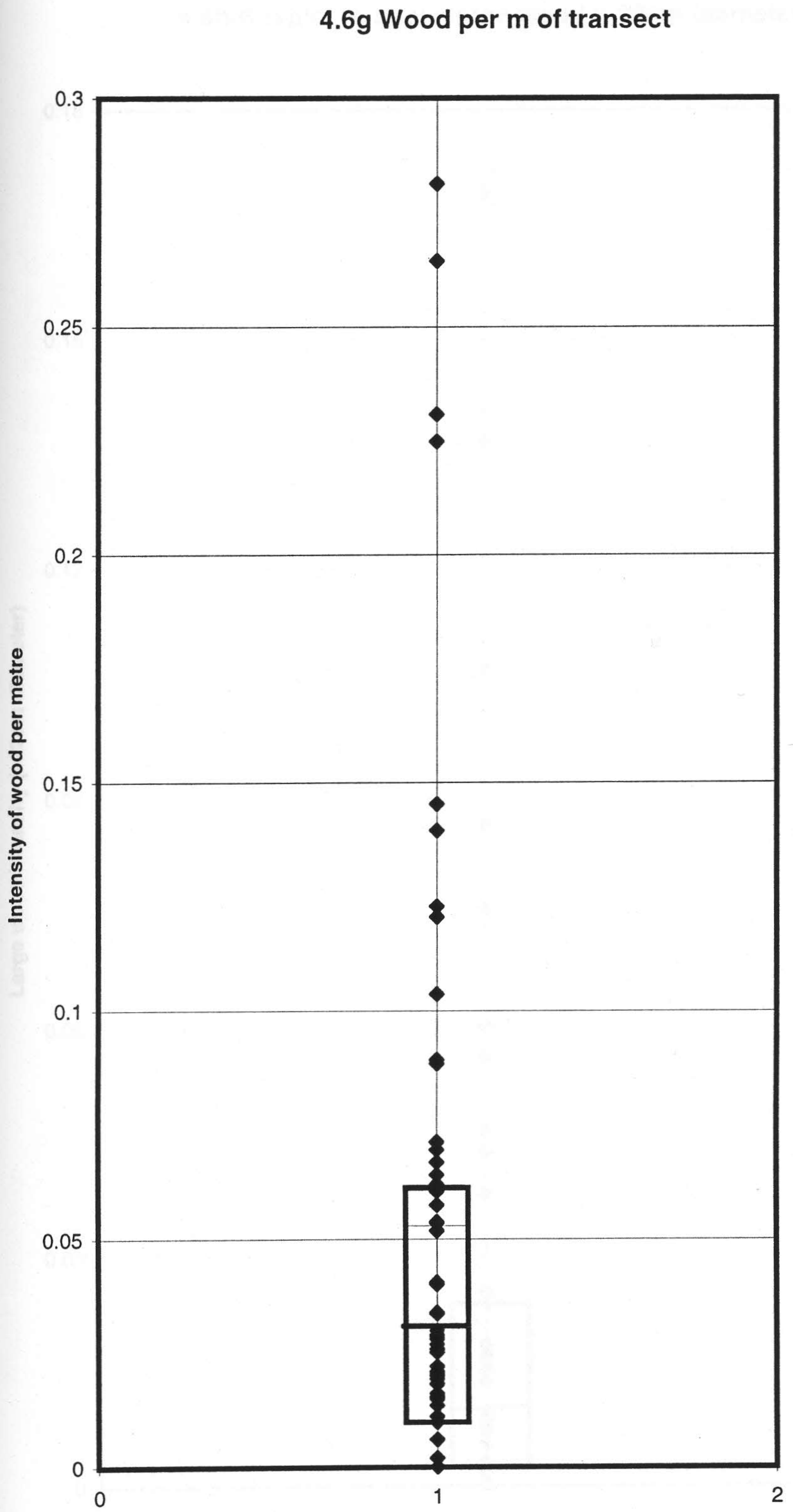
	Correlation	**Critical value of R_s**	**Relationship**	**Signif.?**
Width	0.719	0.269	strong positive	yes
Mapped Width	0.499	0.269	positive	yes
Dune proximity	0.671	0.269	strong positive	yes

Table 4.6c to show Spearman's rank correlation between hypotheses and total wood intensity.

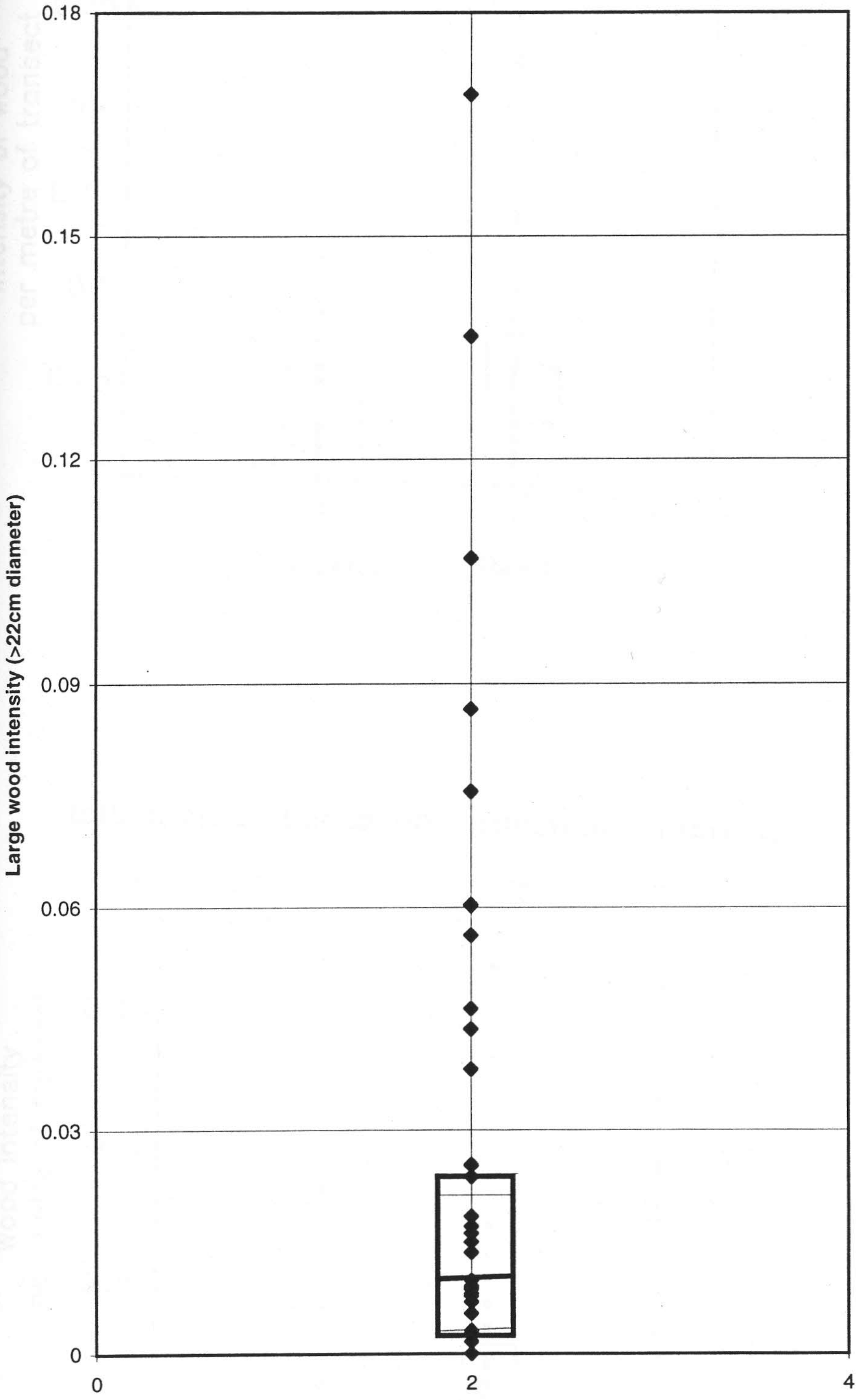
	Correlation	**Critical value of R_s**	**Relationship**	**Signif.?**
Width	0.517	0.269	positive	yes
Mapped Width	0.0703	0.269	very weak	no
Dune proximity	0.374	0.269	weak positive	yes

Table 4.6d to show Spearman's rank correlation between hypotheses and large wood intensity.

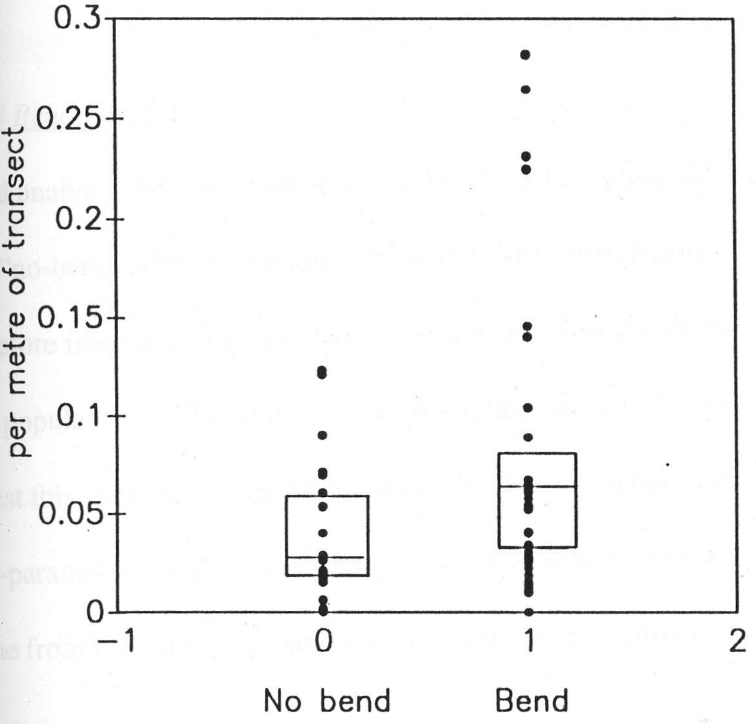
Tables shows calculated correlation coefficient, critical values for R_s at a 95% confidence level, therefore whether the relationships are significant or not. All hypotheses here, barring mapped width against large wood intensity, have a significant correlation with wood. The disparities between the Pearson's and Spearman's correlation are marked. This is likely to be due to the highly skewed data set (see figs. 4.6g and h). The scattergrams show a non-normally distributed data set and a relationship which is non-linear. High magnitude outliers can significantly affect correlation coefficients using interval data, giving undue weight to these data points. The outliers for this set are particularly large, they can be seen on the box plot, and arise from the Weir driftwood deposition site. The ranking involved in the Spearman's correlation attributes equal weight to all data points, reducing the

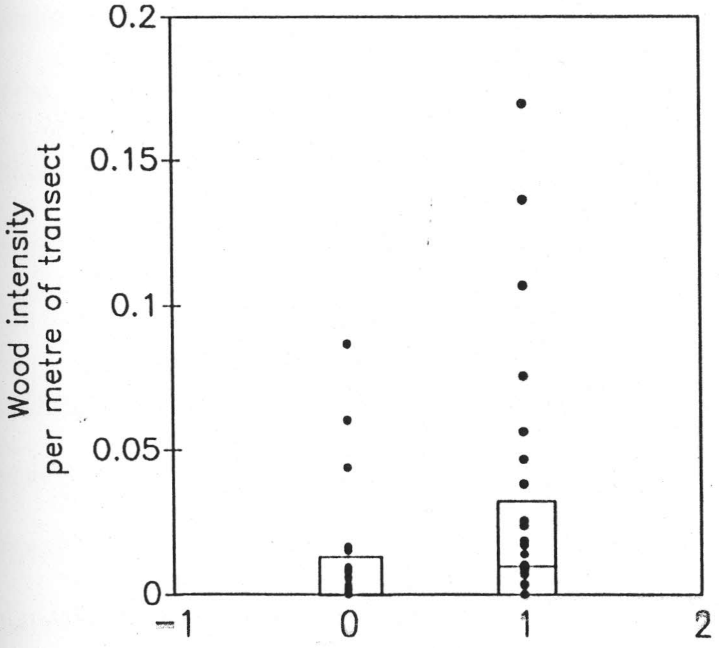

4.6g Wood per m of transect
Intensity of wood per metre
0.3
0.25
0.2
0.15
0.1
0.05
0
0
1
2

4.6h Boxplot to show large wood (>22cm diameter)



Bend analysis


Influence of bends on total driftwood deposition


Influence of bends on large wood intensity

influence of the outlier weir deposit and allowing the relationship between the entire population and hypotheses to emerge.

4.6.4 Bend Data

Bend analysis did not result in interval scale data, instead in two categories of "bend" and "no-bend". Plotting scattergrams and using correlation coefficients were therefore inappropriate. Instead a box plot was drawn (see fig. 4.6e) to compare the two populations. This shows some differences between means, medians and quartiles, to test this statistically the Mann-Whitney U test was performed, appropriate for the non-parametric data. It was found to be 95% certain that the two data sets did not come from the same population, that is were significantly different.

CHAPTER 5: DISCUSSION

5.1. Identifying a spatial pattern in driftwood deposition

The main pattern of deposition perpendicular to the Kuiseb was no significant wood deposition in the channel, and very little further than 200m away. This was as expected, with flood competence for wood exceeding 4cm in diameter not reaching far out onto the 'floodplain' and those deposits which had been emplaced in the channel itself being washed away by subsequent low flows. The contour plots of wood intensity for both total and large wood show no discernible difference between the dune and gravel banks. This was also as expected as areas adjacent to the channel are morphologically similar, and the deposition of wood was expected to be governed predominantly by channel rather than 'floodplain' characteristics.

Notable variations in deposition were in the longitudinal plain, with several indefinite bands of low intensity deposition at intervals downstream. The most impressive deposits were the small compact accumulation at transect 35 (see basemap fig. 1.3e) and the 'weir accumulation'. The deposition of wood along this reach seems therefore to have little pattern, there are areas of interest although they appear to form irregularly following no obvious pattern.

5.2 Explaining the distribution

The attempts made to explain the distribution using multiple hypotheses were more difficult than expected. Subjective and visual methods brought little clarity to the relationships. Statistical methods, however, did provide some insight into possible correlations, but also left several of the hypotheses as possible contenders for explaining the spatial distribution of driftwood. Each hypothesis will be dealt with in turn below.

5.3 Channel widenings and constrictions

5.3.1 Theory: Can channel widenings and constrictions by bedrock cause localised driftwood deposition?

Channel width is normally viewed as the dependant variable, adjusting in response to changes in discharge, velocity, sediment load, and bank resistance (Knighton 1984). This is not always the case, Graf (1983) has shown that width in ephemeral rivers is not necessarily controlled by prevailing conditions. It can be in dis-equilibrium with the present environment and possibly be controlled by higher magnitude events. Wolman and Miller (1957, cited in Richards, 1982), go a step further treating channel width as a controlling variable for channel form and flow. Later, Wolman (1985, in Knighton, 1984) showed how localised abnormalities in channel width could act as the independent variable and produce scatter in downstream hydrology.

Localised sediment deposition depends on changes in the density of water, discharge, velocity and turbulence (Summerfield, 1991; Reinbeck and Singh, 1980). Channel width has the propensity to significantly affect all of these apart from the density of water. Discharge is the product of velocity, depth and width of channel. Given the equation of continuity which states that discharge will remain constant assuming no tributaries, an increase in width will give a corresponding decrease in discharge and therefore, from that, sediment deposition. This, of course assumes that there will be no parallel change in velocity, in response to width alteration. The Manning equation for estimating velocity:

$$v = {}^{1}/_{n} \, (R^{2/3} \, S^{1/2})$$

(where S is slope and R the hydraulic radius, or wetted perimeter divided by cross sectional area) shows that, assuming all other variables constant, an increase in width will give a decrease in velocity, corresponding decrease in energy, and therefore also cause deposition. There is obviously a large body of theory which suggests that channel widening could cause deposition. It would seem that the opposite of widenings, channel constrictions, should not therefore cause deposition. Yet, this is not the case as rapid constrictions in channels can cause an area immediately upstream to decrease in velocity resulting in some sediment deposition. This is known as a 'slackwater deposit'. Similarly constrictions can narrow a channel enough to produce overbank flow, and the higher friction experienced by water travelling on the bank would reduce velocity and cause deposition.

5.2.2. Supporting evidence

There is a body of practical evidence which supports the theory that both channel constrictions and channel widenings can cause deposition, even in flood events. Kochel and Baker (in Baker *et al.*, 1988) in their analysis of palaeoflood slackwater deposits, name dramatic channel widenings and constrictions of the channel by bedrock or talus obstructions as possible causes of the location of deposition. Further supporting evidence can be gained from research undertaken in this study area. The cause of the 20 000 year old fluvially deposited fine grained silts known as the Homeb silts in the 'Canyon Section' (Marker, 1977) of the Kuiseb, has sparked much contention. There are theories which support localised channel widenings, embayments or tributary mouths as a cause flood deposition (Smith, 1992; Ollier, 1977), as well as those which support channel constrictions by bedrock as the cause (Smith, 1992).

5.2.3. Do channel widenings or constrictions cause flood driftwood deposition in this area?

Since these hypotheses were tested using the same data set, it is therefore appropriate to deal with the affect of widenings and constrictions on deposition simultaneously. Subjectively comparing areas of bankful channel widening from field measurements, channel width from the map, and a contour plot from surveying data with plots of total and large wood deposition, produced little obvious correlation.

Scattergrams (figs. 4.6a-c and d-f) also show little or no relationship between variables. Although when a Spearman's Rank correlation was performed, a reasonably strong positive correlation, at 0.719, was found between field observed width and deposition, significant at 95%. A lower, but still significant correlation of 0.498 was found between map determined width and wood intensity. Therefore, as channel width increases so does intensity of total and large wood. Immediately this rejects bedrock constrictions as a possible cause of the deposition, and gives more weight to the widenings hypothesis. This was surprising as in the field it appeared that wood was commonly deposited on or behind bedrock outcrops (see photograph 4.1a and 4.1b), and in places of wide channels, especially with the high deposition sited at transect 35 and at the weir. The increase in occurrence of large wood seems logical as widenings would produce a reduction in velocity, discharge and depth of flow, this would be likely to cause deposition. The lack of any visual relationship, followed by a fairly strong correlation indicates that the influence of channel widenings on driftwood location is probably a non-linear one, possibly influenced by threshold widths above which deposition is affected, 2.6.4 explains the effect this can have on these statistical tests.

The possibility that this result occurred by chance is eliminated by testing for significance, although the effect on the sample population of the wide channel at the Weir site where there was very high deposition cannot be eliminated. To test for this these readings could be eliminated and the coefficient re-calculated. A more scientifically sound way would be to investigate a much longer reach of river, this may uncover more sites of the weir kind reinforcing the pattern, or none at all reducing its influence.

5.4 Bends

5.3.1. Theory: Could channel bends cause localised driftwood deposition?

Again, this channel characteristic is most commonly seen as a dependent variable. Channel pattern is thought to be controlled by stream power reflecting discharge and sediment load (Chorley, 1984), and also features like riffle and pool sequences (Wolman 1957 in Richards 1982). In some situations, however, bends can be influential in channel processes. Localised deposits such as point bars, are known to be affected by bends. This erosion and deposition pattern depends on the complex system of primary and secondary currents (Richards 1982), with a high velocity thread directed towards the outer bank at the surface and the inner bank at the bed causing an area of slower water and deposition. Conditions may change during a flood event, Russell (1967 in Kessel) documents the movement of the thread of maximum velocity to the convex bank in a flood stage.

5.3.2. Supporting evidence

Correlation between bends and localised deposits has been documented by Ritter (in Baker *et al.*, 1977) where the most common depositional feature found after the 1982 floods in south-east Mississippi were bar like lobes of sand and gravel, predominant inside bends. The presumption was that sediment had formed a ramp on the bend during the high flow, which allowed sediment to move onto the floodplain. Similarly, Kessel *et al.* (1974) note that the thickest and coarsest overbank deposit of between 80 and 1.2m laid down in the 1973 Floods on the Mississippi River were located on natural levees and on the convex banks of curves, rather than the straight areas. Velekanova and Yarnykh (1970) noted that the thickest layer of sediment laid down on the Bystraya arm of the Ob' river, during a particular flood event on was on the convex banks of the curve.

5.3.3. General planform characteristics of the Kuiseb

In general the Kuiseb shows a highly meandering character, with braiding in some reaches, especially downstream from the site of this study. Even in the sample reach there are five to six major bends and countless small ones, shown clearly on the Gemini V satellite image (fig. 1.3f).

5.3.4. Do channel bends cause localised driftwood deposition?

Subjective comparison between bend areas and deposition, both in the field and from results showed no obvious relationship. The boxplot created to represent the data graphically did, however, imply a relationship with higher medians and quartiles for bend areas than non-bend areas, certainly for total wood. The bend sample had consistently higher wood intensities then the non-bend group, both for bend and non bend results. The quartile deviation for all plots showed a fairly tight distribution indicating little influence of outliers on the result.

The Mann-Whitney U test helped to verify these findings. It is 95% certain that bend and no-bend sample sets did not come from the same population, that is that they are significantly different. This implies that deposition on bends is different, and from the diagram, higher than on non-bend reaches.

It must be noted that the sample size of 163 data points for taking azimuths was not particularly large, and that the channel was predominantly curved rather than straight along its course, it could be that this sample reach was not representative of the rest of the river, where there might be more straight reaches to give a larger population. To verify this hypothesis a larger stretch of channel would have to be surveyed, and the interpolation of points and measures of azimuth undertaken by computer (in Goudie, 1989). It is unfortunate that the measures of bends were not interval scale data, this precluded the use of correlation coefficient, and therefore it can only be established that there is a relationship, and from the box plot its direction, not its strength.

5.4 Partial damming of channel by dunes.

5.4.1. Theory

Dune damming of a river is a fairly specialised process, requiring particular environmental conditions found on the Kuiseb. Hence there has been no large body of work on this subject. Theoretically it should act like the constriction of the channel by bedrock, creating a slackwater area behind it or overbank deposition although the dune will possibly be more porous and less resistant.

There is little evidence that the dunes have ever completely traversed the channel in this stretch, as they have at the delta. It is thought, however, that given enough time when river flows are not regular or strong enough to remove the sand, they can intrude onto it. This highlights a current concern, that if extraction is increased upstream by commercial and subsistence farming, and rainfall continues to be low, the lack of water, and the die-back of vegetation, will allow dunes to completely traverse the river.

> "During flood events the Kuiseb river carries along its course great amounts of sand which have blown in during the dry period" (Seely and Sandelowsky, 1974)

5.4.2. Evidence

There is evidence that partial damming by dunes has caused deposition before in this area. The dune damming mechanism has been put forward as a possible cause for the deposition of the Homeb silts. Rust and Weinecke (1978, 1980) Scholtz (1968) and Goudie (1972) showed how the silts were laid down whilst the Kuiseb was blocked by dunes during a more arid phase. Marker and Müller (1978), Marker (1982) and Vogel (1982) rejected this explanation, maintaining that the river dried up first in an extreme arid phase whilst the Benguela current became established, and the dunes moved across after that.

5.4.3. General Dune Characteristics of the area

This part of the Namib has complex linear dune formations, the satellite photograph shows this especially clearly. They stretch over a large expanse of the Namib and are only stopped by the Kuiseb in the north. The dune formations are typically of 80-100m in height, and trend north to south (Goudie, 1972). Their direction and rate of movement is governed by the wind patterns in the area, equally strong winds in several directions lead to linear forms.

5.4.4. Does dune damming cause driftwood deposition in this area?

There is no reliable way to assess whether dunes have crossed the Kuiseb within the time period when driftwood is still intact. However, Vogel (1981) has some of the driftwood deposits in this area dated at 1660AD indicating that these are reasonably permanent features as the time to cross the Kuiseb has been calculated at 10 years. (Lancaster).

Subjective correlation between areas that were postulated to be at risk from dune damming was inconclusive. The index of possible damming, distance to dune, correlated strongly and positively (0.671) with total wood intensity and weakly, but nevertheless significantly with large wood, with a coefficient of 0.374. This indicates that dunes further away have more of relationship with deposition, if dunes had dammed the river the expected result would be that close dunes cause higher deposition, a strong negative correlation. The dune damming hypothesis was therefore rejected. The possible reasons for this surprising result will be expanded under 6.1.

The method of investigation into this was not ideal, there is no method to asses when and where dunes might have dammed the river, with the possible exception of careful analysis of sediment cores on the gravel bank to find evidence of large quantities of dune sand. The indicator of dune proximity was worth testing, perhaps further work should include statistical analysis of dune movement, wind directions and dune orientation.

5.5 Summary

The hypotheses of channel constriction by bedrock and partial dune damming influencing the spatial distribution of driftwood had to be rejected. This has left channel widenings and channel bends as a possible causes, although they could not be compared in the same statistical manner to make assumptions as to which is the most important.

CHAPTER 6: CONCLUSION:

6.1 General conclusions:

The overarching aim of the study was to define the causes of the spatial distribution of driftwood. This investigation has certainly made an advance in this. There was, however, little or no discovery of a regular pattern in driftwood sedimentation during high magnitude flood events. The generalisations which can be made are that there is very little wood, certainly no large wood, within channel boundaries, and little deposition beyond about 300m from the channel. No distinguishable difference between dune and gravel banks was found. Longitudinally, deposits are irregularly spaced with bands of low deposition and no deposition. The main high intensity areas were at transect 35, at the Wier accumulation and the Weir to Soutriviere band.

Explanation of this pattern involved the investigation of multiple hypotheses: distribution is caused by channel widenings, by channel constrictions by bedrock, by channel bends, or by partial dune damming of the river. Statistical and qualitative analyses showed that two hypotheses were unlikely to be the cause of the pattern. At a 95% confidence level, total wood intensity was strongly correlated to channel width, implying, therefore, that areas of low channel width, or channel constrictions were not related to high deposition of wood during floods. Strong correlations are, of course not synonymous with a causal relation, they merely identify a relationship. It has to be pointed out that one hypothesis was that areas of localised channel constriction would cause deposition, this does not support analysis in a linear manner, and it is possible that at a specific threshold width, below which channel depositional environment changes dramatically, substantial deposition can be triggered.

The hypothesis that dune damming explained the distribution of driftwood could also be rejected. When the best index of dune damming, proximity, was correlated with wood intensity and large wood intensity it gave a positive correlation indicating that the further the dune, the more large clasts and the higher the intensity of wood. This is completely the reverse of what was expected, that closer dunes would have dammed the river most recently and caused deposition. The apparent variation in this could possibly be explained by the influence of other variables such as channel width or bends on intensity figure, which happened to correlate with dune areas. It is also likely that in areas of distant dunes, channel width is higher and this is the true cause of the higher deposition in this area.

The other two hypotheses can be tentatively accepted. For channel widenings, as has been stated above, the correlation was strong and positive. Indicating wider channels generally relate to more large wood and higher total intensity. This was significant at the 95% confidence level. Channel bends causing deposition can be accepted, as the "no-bend" and "bend" populations proved to be significantly different. However, the lack of a correlation coefficient meant that channel bends could not be compared in the same way as the other hypotheses.

It is possible that the causal mechanisms do not act independently. This would upset the simple multiple hypothesis format of this study, where variables are considered to affect deposition separately and independently. In the field there seemed to be a pattern of proximate dunes correlated with low channel width, bedrock outcrops initiating bends and widenings associated with particular points on bends. Although four hypotheses were selected for testing in this reach, they are not necessarily exhaustive, there may be one or a combination of other channel or floodplain variables which affect the distribution of driftwood. Impressions gained from the field suggest that large scale riffles are prime contenders for causing deposition. Also on a localised scale bedrock mounds may significantly slow the water, causing wood deposition on top or just behind them, even though they are not large enough to divert the whole channel. Isolating the real cause or causes behind the distribution requires additional work, testing new hypotheses and looking into chains of causation.

This study has improved the understanding of the spatial distribution of driftwood deposition during high magnitude flood events. This can have ramifications for example in the understanding of sediment sequences. By highlighting how and under what environmental conditions plant macrofossils enter sediment sequences, and whether they were remobilised after death, their radiocarbon dates can be put into context and enable more accurate reconstruction of the whole profile. The investigation has also unveiled new research needs and approaches which can improve upon previous work. The processes operating on the Kuiseb have been seen to reinforce studies carried out on similar rivers, as expanded in the introduction and discussion chapters

6.2 Critique of Methodology and suggestions for future research.

The reach of the Kuiseb surveyed was 15km in length. This was the maximum size feasible given the time constraints during the field study. Combined with the spacing of the transects this gave only a small population on which to work on. Ideally the whole valley section should have been surveyed, this would have reduced the importance of localised high intensity deposits like the weir site, if they were anomalous, and reinforced them if they were a regular feature. In a similar way comparison with driftwood deposition on other dryland rivers would have improved accuracy.

The transect method proved successful for gaining an overview of the section. Early on in the study, however, it was found that these left large gaps in the recorded deposition, skewing the pattern unnaturally. Later during the contour plotting these were filled in statistically, making assumptions about the 260m in between the areas surveyed. Transects would have been better sited at 50m intervals where gaps in records would be negligible. Instead the whole area could be assessed on a grid basis.

With the greater understanding of the deposition processes, provided by time spent in the field, I would now suggest that overall coverage of a reach using transects should be sacrificed for small scale mapping of the features within a particular high magnitude deposit over a longer reach. Locations should be found from tape and compass data, or possibly even using a satellite positioning system. The limited area surveyed by tape and compass, at the weir, proved relatively successful.

The lack of indication of which deposits were brought down in which floods hampered progress into understanding flood size and where wood was distributed. Relative age impressions proved to be not particularly useful, more knowledge of the decomposition processes of wood in drylands was needed. Instead Radiocarbon dating could be employed, Vogel and Visser (1981) have carried some of this out in the area dating some deposits to the 1450s, whether the accuracy of this technique at such short timescales justifies the expense is debatable. Other historical records of flooding needed to be found, to develop the timeline further.

The detailed wood data, apart from diameter, was not used to its full potential. This broad nature of the study meant that some avenues were left uninvestigated. If deposits were mapped carefully, relative spacing of logs and orientation could give vital insights into the flow characteristics of the floods. It must also be pointed out that log shape and size was affected by decomposition, and often splitting into smaller sections, influencing the view taken of flood competence.

It became obvious that the channel of high magnitude flood stage would have been more useful. This would have allowed flood river height to be drawn onto the surface or contour plot. From this constrictions and widenings could be inferred. A larger body of data would have benefited the "SURFER" plot, giving a more accurate plot. The survey should also have been continued to at least 800m from the channel to include wash tributaries and dune characteristics, by means of the more modern quickset level.

Bend analysis worked relatively well. Ideally an aerial photograph of a larger scale could have been used, and the interpolation of points carried out on a computer. At distances of 1-2 channel widths between centres, this would have given more precise results. Unfortunately no matter how precise the azimuth/path distance plot is, it still must be interpreted subjectively. It would be interesting to investigate some other bend characteristics such as radius of curvature or wavelength between bends, as this could be more easily correlated with wood data.

Dune damming was a difficult variable to assess. Improvements on the method could be gained by measuring rate and direction of movement along the dune, and possibly taking sedimentary cores of the river bed to determine if dunes blocked the river at a particular time.

6.3 Research sucess

In sum, the investigation of four hypotheses involved some compromise in the level of detail which could be directed on each. Nonetheless focus on all four proved very illuminating, allowing a general picture of some key controls on driftwood deposition to be highlighted and other hypotheses to be ruled out. Channel widenings was found to be the most important hypothesis, although the non-linearity of the correlation precludes precise description of the relationship. Further research is now needed to constrain the relative role of each hypothesis more effectively and bring new relationships to light.

BIBLIOGRAPHY

Abrahams, A. P. and Parsons, J. P. (1994) The Geomorphology of Desert Environments Cambridge University Press

Baker, V. R. Kochel, R. C. and Patton, P. C. (1988) Flood Geomorphology John Wiley and Sons

Baker, V. R. (1977) Stream channel response to floods,with examples from central Texas Geological Society of America 88 1057-71

Baker, V. R., Kochel, R. C. and Patton, P. C. (1988) Flood Geomorphology. John Wiley and Sons

Bate, G. C.; Walker, B. H. (1993) Water relations of the vegetation along the Kuiseb river, Namibia Madoqua 18 (2) pp 85-91

Berry, C. U. (1995) (unpub.) Unpublished data on the Kuiseb river system in the Namib-Naukluft Park

Beven, K. Carling, P. (1989) Floods: Hydrological, sedimentological and geomorphological implications American Journal of Science 292 (9) pp 724

Brain C. K. (1984) Comments on the Namib's past South African Journal of Science 80 pp 158-159

Butcher, G. C. Thornes, J. B. (1978) Spatial variability in runoff processes in ephemeral channels Zeitshcrift für Geomorphologie Supplementband 29 pp 83-92

Calow, P. and Petts G. E. (1992) The rivers handbook Blackwell

Chorley, R. J., Schumm, S. A. and Sugden, D. E. (1984) Geomorphology Cambridge

Cooke, R. Warren, and Goudie Desert Geomorphology

Costa, J. E. (1974) Stratigraphic, Morphologic and Pedologic evidence for large

Costa, J. E. (1983) Palaeohydrological reconstruction of flash flood peaks from boulder deposits in the Colorado Front Range Bulletin of the Geological Society of America pp 986-1004

→ **Crerar** (1987) An unexpected factor affecting recharge from ephemeral flow SWA

Dausab, F. et. al. (1994) Water usage patterns in the Kuiseb catchment area unpublished Desert Ecological Research Unit of Namibia paper

Ebdon, D. (1985) 2nd edn. Statistics in geography Basil Blackwell

floods in humid environments Geology 2 (6) 301-303

Frostick and Reid (1985) The incidence and nature of bedload transport during flood flows in coarse gravel colluvium Earth Surface Processes and Landforms 10 (1) pp 33-41

Golden Software inc. (1994) Surfer for windows: user guide

→**Goudie, A. S.** (1972) Climate, weathering, crust formation, dunes and fluvial features of the central Namib Desert, near Gobabeb SWA. Madoqua II 1 (54-62) pp15-31

Graf, W. L. (1983) Flood related channel change in an arid region river

Graf, W. L. (1988) Fluvial Processes in Dryland Rivers Springer-Verlag

Gregory, K. J. and Walling, D. E. (1973) River channels John Wiley and sons

Gupta, A. (1983) High Magnitude floods and stream channel response Special publications of the international assocaition of sedimentologists 6 pp 219-227

Heine, K. (1985) Late quaternary development of the Kuiseb River valley and adjacent areas, central Namib desert, SWA/Namibia and palaeoclimatic implications Zeitschrift für Gletscherkunde 21 pp 151-157

Heyns, P. S. (1990) (unpub) Episodic flood events of rivers crossing the desert Presented at the episodic events and natural resources workshop 26th October, Alte fest, Windhoek, Namibia

Huntley (1987) The kuiseb environment: a monitoring baseline

Jacobson, Seely, M. K. (1994) Ephemeral rivers and their catchments

Keller, K. A. and Swanson, F. J. (1979) Effects of large organic material on channel form and fluvial process Earth Surface Processes 4 (4) pp 361-380

Kessel, R. H., Dunne, K. C. McDonald, R. C., Allison, K. R. and Spicer, B. E. (1974) lateral eroaion and overbank deposition on the Mississippi River in Louisiana, Geology 2 (9) pp 461-464

Knighton, A. D. (1984) Fluvial Forms and Processes Arnold

Koch, C. (1963) An illustrated account of a major flood in the kuiseb river Sonderdruck aus der Kreis 2/3 Februar März

Labib, T, M, (1981) Soil erosion and total denudation due to flash floods in the Egyptian Eastern Desert Journal of Arid Environments 4 pp 191-202

Leopold, L. B. Wolman, M. G. and Miller, J. P. (1964) Fluvial Processes in Geomorphology

Lewin, J (1978) Floodplain geomorphology Progress in Physical Geography 2 (3) pp 403-437

Lewin, J. (1992) Floodplain construction and erosion in Calow and Petts (1992) The rivers handbook

Marker, M. E. (1977) A long return geomorphic event in the Namib Desert, SWA Institute of British Geographers 9 (3) pp 209-213

Marker, M. E. (1977) Aspects of the geomorphology of the Kuiseb River S.W.A. Madoqua 10 (3) pp 199-206

McKee, E. B., Crosby, E. J. Berryhill, H. L. (1967) Flood deposits, Bijou Creek, Colerado Journal of Sedimentary Petrology 37 (3) pp 829-851

Newson, (1980) The geomorphic effects of two floods a sintribution stimulated by two recent events in mid-wales Earth Surface Processes and Landforms 5 (1) pp 1-16

Ollier (1977) outline geological and geomorphological history of the central Namib desert Madoqua 10 (3) pp 207-211

Popov, L. V. and Gavrin, Yu. S. (1970) Use of aerial photography in evaluating the flooding and empting of river flood plains and the development of floodplain currents, Soviet Hydrology 5 pp 413-425

Reid and Laronne (1995) Bed Load Sediment transport in and ephemeral stream and a comparisonwith seasonal and perrenial counterparts. Water resources research 31 (3) pp 7733 - 781

Reinbeck, H. E. and Singh, I. B. (1980) Depositional sedimentary environments Marine Geology 46 (3-4) pp 348

Richards, K (1982) Rivers: Form and Process in Alluvial Channels Methuen, London

Ritter, D. F. (1975) Stratigraphic implications of coarse grained gravel deposited as overbank sediment, South Illinois Journal of Geology 83 pp 645-65

Seely, M. K. (1984) The Namib's place among deserts of the worl South African Journal of Science 80 pp 155-155

Seely, M. K. And Sandelowsky, B. H. (1974) Dating the regression of a river's end point South African Archeological Bulletin, Goodwin Series (2) 61-64

Seely, M. K.; Buskirk, W. M.; Hamilton, W. J.the 3rd, Dixon, J. E. W. (1979) Lower Kuiseb river perrenial vegetation survey South West African Scientific Society Journal 34 pp57-82

Selby, M. J. (1976) Some thoughts on the geomorphology of the Central Namib Desert Namib Bulletin - supplement 1 to the Transvaal Museum Bulletin

South African Journal of Science, 77, (1981) Ancient climates and the age of the Namib

Stear, W. M. (1985) Comparison of the bedform distribution and dynamics of modern and ancient sandy ephemeral flood deposits in the south-west Karoo region, South Africa Sedimentary Geology 45 pp 209

Stene, L. P. (1980) Observations on lateral and overbank deposition, evidence from Holocene terraces, South west Alberta Geology 8 pp 314-315

Stengel, H. W. (1964) Die Rivere der Namib und Ihr Zulauf zum Atlantik Scientific Paper of the Namib Desert Research Station 22 III

→ **Stengel, H. W.** (1986) (unpub) The source of drinking water at Gobabeb unpublished Desert Ecological Research Unit of Namibia paper

Stengel, H. W. (unpub.) Das abkommen des Kuiseb und Swakop für die Zeit von 1898-1938

Summerfield, M. A. (1991) Global Geomorphology Longman scientific and technical, Harlow

Thomas, D. S. G. (1989) Arid Zone Geomorphology Belhaven

Van Zyl, J. A. (1992) The major landform regions of Namibia South African Geographer 19 (1/2) pp 76-90

→ **Van Zyl, J. A. and Scheepers, A. C. T**. (1992) The geomorphic history and landforms of the lower Koigab river, Namibia South African Geographer 20 (1/2) pp 12-22

Velikanova, Z. M. and Yarnykh, N. A. (1970) Field investigations of the hydraulics of a flood plain during a high flood Soviet Hydrology 5 pp 426-440

Vogel, J. C. and Visser, E. (1981) Pretoria Radiocarbon dated II Radiocarbon 23 (1) pp 43-80

Ward, J. D., Seely, M. K. and Lancaster, N. (1983) On the antiquity of the Namib South African Journal of Science 79 pp 175-182

Ward, R. (1978) Floods: A geographical perspective Macmillan

Waythomas, C. F. and Jarrett, R. D. (1994) Flood Geomorphology of Arthur's Rock Gulch, Colorado: palaeoflood history Geomorphology 11 pp 15-40

Williams, G. E. (1971) Flood deposits of the sand bed ephemeral streams of central Australia Sedimentology 17 pp 1-40

Williams and Costa