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SOURCES OF SEDIMENTS ACCUMULATING IN THE LOWER BLACK AND VYGEKRAAL RIVERS, CAPE TOWN, SOUTH AFRICA

by

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Submitted in partial fulfilment of
the requirements for the degree of
Master of Philosophy,
in the Department of
Environmental and Geographical Science,
University of Cape Town.

1991

ACKNOWLEDGEMENTS

The author would like to thank the following persons and organisations for their assistance during the compilation of this thesis:

1. The South African Breweries, the Harry Crossley Foundation and the Cape Town City Council for their financial contributions toward the study.

2. Professor R F Fuggle for his supervision of the research.

3. Mr P J Holmes of the Department of Environmental and Geographical Science (University of Cape Town) for his guidance regarding the analytical part of the project.

4. Mr G Boddington and Dr J A Thornton of the Cape Town City Council for introducing the author to the study topic, and for providing advice at numerous stages throughout the research.

5. Mr A Vinnicombe for his assistance with the drafting of illustrations.

6. Mrs E Pellew for the desk-top publishing.

7. Dr R T Watkins, Dr H Frimmel and Professor W E L Minter of the Department of Mineralogy and Geology; Professor J P Willis of the Department of Geochemistry; and Dr J Rogers of the Marine Geoscience Unit (all University of Cape Town) for their advice during different stages of the research.

8. Mr M E Smith of the Marine Geoscience Unit; and Mr P Shepherd and Mr C P Basson of the Department of Mineralogy and Geology (both University of Cape Town), for their assistance with particle size analyses, X-ray diffraction, and microphotography, respectively.

9. The Department of Chemical Engineering (University of Cape Town) for the use of equipment.

10. Mr G Stavridis of the Cape Town City Council, and staff of the Department of Computer Science (University of Cape Town), for assistance in the running of SAS and BMDP statistical programmes, respectively.

11. Personnel in the Scientific Services and Drainage and Sewerage Branches, and the Municipal Reference Library (all of the Cape Town City Council) for their help in answering requests from the author.

12. Ms M McIntosh of the C.S.I.R., and staff of the Department of Water Affairs and the Hydrological Research Institute, for undertaking computer-based literature searches at the author's request.

13. Ninham Shand Inc., for making reports of theirs available to the author.

14. Mr C A R Bain of the Atomic Energy Corporation, and Professor K A Viewing of the Anglo American Corporation (Harare), for their thoughts on further research into the topic.

ABSTRACT

Soil erosion within the catchment areas of the Black, Vygekraal and Elsieskraal Rivers (Cape Town, South Africa) results in sediment transport by these rivers, their tributaries, and the stormwater drainage systems which flow into these rivers. This sedimentary material is subsequently deposited in the lower reaches of the Black and Vygekraal Rivers owing to a decrease in the competence of the watercourse in this area. The resultant accumulation of sediment necessitates costly annual dredging of this section of river (referred to in this study as the "dredged area") by the Cape Town City Council.

The loss of soil cover within the three catchments is initiated mainly by wind in summer, and by rain in winter. Soil erosion is likely to be of greatest magnitude in the Vygekraal catchment, owing to the extensive exposure of the natural sand cover as a result of poorly vegetated areas. Steep slopes, and construction works linked to urban development, also render the upper parts of the Elsieskraal catchment vulnerable to soil erosion. A relatively insignificant amount of soil loss is believed to occur within the catchment of the Black River.

Measurements and estimations of the relative transporting powers of the Black, Vygekraal and Elsieskraal Rivers showed that the Vygekraal River was likely to have the greatest capacity to transport sediment throughout the year, while the Black River would have the least capacity. Particle size analyses of the watercourse sediments in the study area showed that the sands of the Cape Flats, i.e., within the Vygekraal catchment area, were the most easily transported sediments in the study area, by both water and wind. Finer alluvial sediments in the Tygerberg Hills region (in the upper Elsieskraal catchment), directly derived from the loam soils of the area, were also found to be easily transported by natural elements. The coarser sediments in the Black River catchment were probably transported at a significantly slower rate, than were the fine sediments of the Elsieskraal River, and the medium-grained sands in the Vygekraal catchment area.

X-ray diffraction analysis of the clay component of the sediments indicated that the sediments accumulating in the extreme lower sector of the dredged area probably had their source in the upper Elsieskraal catchment area. Microscopic studies of the modal sand fractions of the sediments showed that it was likely that the sediments deposited in the upper and middle parts of the dredged area were almost exclusively derived from the catchment of the Vygekraal River, while the sediments in the lower part of the dredged area were equally likely to have originated from either of the three catchments.

Multivariate statistical analyses were performed on the data set comprising the variables generated by the particle size analyses. The results from these investigations showed that, for the dredged area as a whole, the largest contribution of sediment came from the Vygekraal River, with the least from the Black River. The proportionate contribution of the Elsieskraal River to the total sediment accumulation in the dredged area is likely, therefore, to be intermediate to those from the Vygekraal and Black Rivers.

Further, more detailed studies of sediment transport and soil loss would be necessary in order to accurately determine the percentage contribution of each of the Vygekraal, Elsieskraal and Black Rivers to the total quantity of sediment accumulating annually in the dredged area.

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LIST OF ABBREVIATIONS AND SYMBOLS

B, BLA:	Black River (or Canal)
V, VYG:	Vygekraal River (or Canal)
E, ELS:	Elsieskraal River (or Canal)
U:	Upper dredged area
M:	Middle dredged area
L:	Lower dredged area
X:	Extreme lower dredged area
BLO:	Blomvlei Canal
BOK:	Bokmakirie Canal
JAK:	Jakkalsvlei River
KAL:	Kalksteenfontein River (or Canal)
KRO:	Kromboom Canal
km:	kilometres
m:	metres
cm:	centimetres
mm:	millimetres
kg:	kilograms
g:	grams
s:	seconds
cumec:	cubic metres per second
°:	degrees
%:	percentage
XRD:	X-ray diffraction
Å:	Angstrom units
X:	linear magnification factor for microphotographs
ϕ:	phi units

ϕ units		grain size (mm)
-1	=	2,0
0	=	1,0
1	=	0,5
2	=	0,25
3	=	0,125
4	=	0,0625

CHAPTER 1 : INTRODUCTION

1.1 INTRODUCTION TO THE STUDY

1.1.1 The problem of sediment transport, deposition and dredging

Sediment accumulation in the lower reaches of the Black and Vygekraal Rivers between the Jan Smuts Drive bridge (Athlone), and the Black River Parkway bridge (Observatory), results in the need for costly annual dredging of some 3,9 km of river course over a width of 20 m to 40 m. According to the Annual Report of the Cape Town City Engineer (1988/89) there are plans to widen this stretch of river, particularly in the vicinity of the Rondebosch Golf Club. This section of watercourse is hereafter referred to as "the dredged area".

The lower Black and Vygekraal Rivers which comprise the dredged area are, in fact, the same watercourse. The upstream Vygekraal sector of the channel ends at the point where the Black River canal, which drains the eastern parts of the Rondebosch/Claremont area, enters the dredged area, at the Rondebosch Golf Course. The Vygekraal River's catchment area covers the north-western sector of the Cape Flats. The Elsieskraal River, which enters the lower Vygekraal River some 700 m upstream of the Vygekraal/Black confluence but 600 m downstream of the upper limit of the dredged area, is responsible for the drainage of the Tygerberg Hills/Bellville/Parow/Goodwood region. The study area comprises the entire catchment area of the Black/Vygekraal/Elsieskraal system (Figure 1).

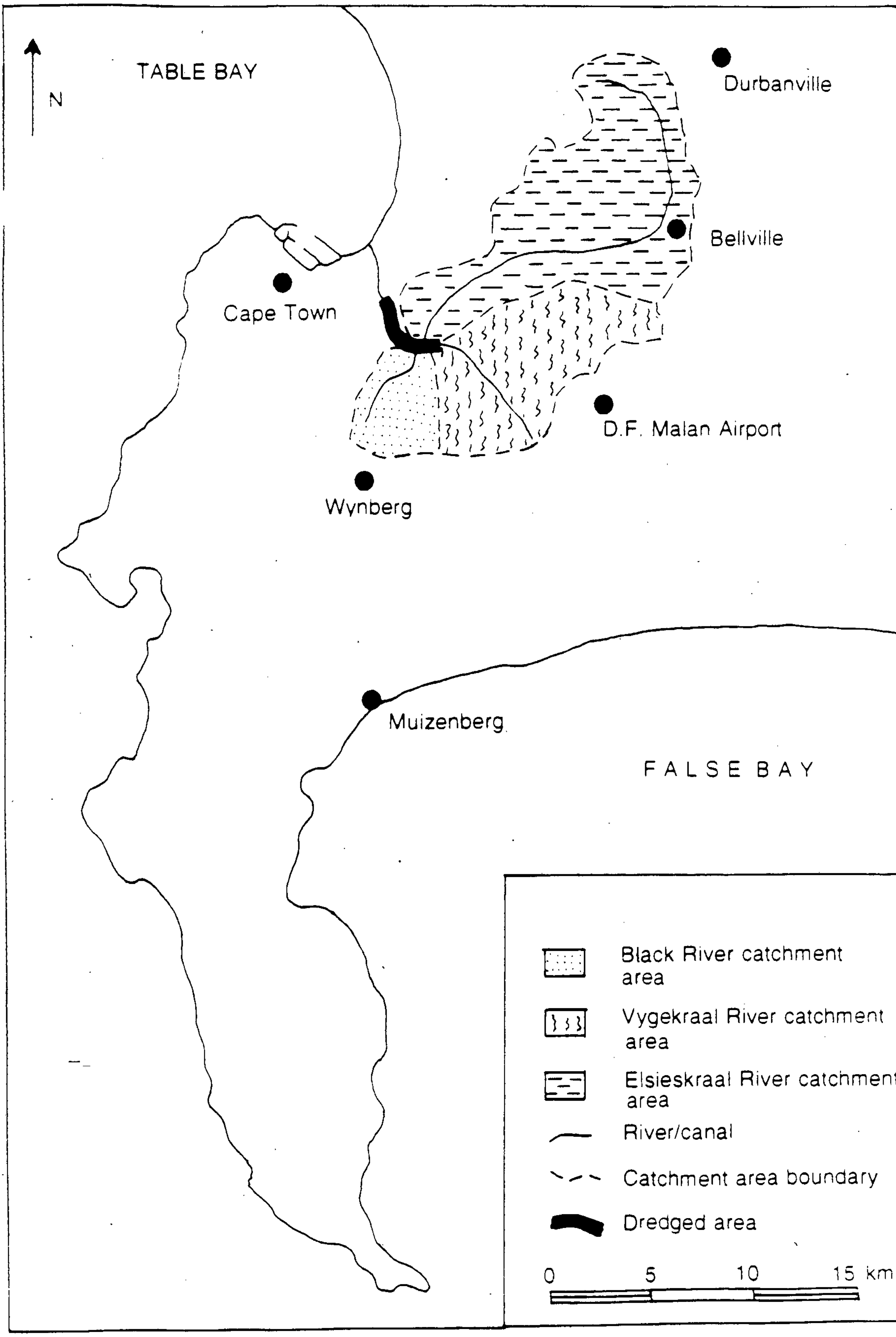


Figure 1 : Location of Study Area

Sediment deposition is most rapid in the upper 2,4 km of the dredged area, i.e., between Jan Smuts Drive (Athlone) and Raapenberg Road (Mowbray/Pinelands), especially immediately downstream of the Vygekraal/Elsieskraal confluence (City Engineer's Dept., pers.comm.). This 2,4 km section is dredged annually during the autumn months; for example, some 10 800 cubic metres of sediment was removed from it between 26th March and 1st June 1990 (City Engineer's Dept., pers.comm.). Sediment accumulation occurs at a lesser rate in the lower 1,5 km of the dredged area, i.e., between Raapenberg Road and the Black River Parkway bridge (Observatory), and, as a result, this stretch of river is only dredged once every 2 or 3 years (City Engineer's Dept., pers. comm.).

Soil erosion, and removal of the surface sand cover, followed by transportation of this material, in the catchment areas of the Black, Vygekraal and Elsieskraal Rivers, leads to sediments entering the stormwater drainage system. From the drains, the sediments are transported through culverts which lead into the Black, Vygekraal and Elsieskraal Rivers, and their tributaries. The main agents of soil and sand mobilization within these catchment areas are water (rain, overland flow and strongly running watercourses) during the winter months, and wind throughout the dry summer months.

Although some organic matter is present, the sediments comprise mainly sand (almost entirely quartz), with minor components of gravel, silt and clay. Some of the samples collected and analysed also displayed small fragments of materials of anthropogenic origins, such as concrete, brick, glass, and road aggregate. This study will, by means of various geological (sedimentological) and statistical techniques, endeavour to determine the places of origin (in terms of sub-catchment areas) of the sediments which are accumulating in the lower Black and Vygekraal Rivers.

1.1.2 Academic motivation for the study

The lack of previous research into the sedimentology and hydrology of the Black River system has prompted this study. Although there is a reasonably large amount of literature available on the geology, climate and land use, very little has been researched and written on the actual sediments of the rivers and canals within the catchment area of the Black River system, in terms of either descriptions or provenance of the sediments. Numerous sedimentology texts exist, but not all of these are necessarily directly applicable to the questions that need to be answered by the findings of this study. An appraisal of the literature used in the research for the study follows.

1.1.2.1 Previous research on the Black/Vygekraal/Elsieskraal system

Very little data exists on the sedimentology and hydrology of the catchment systems of the Black, Vygekraal and Elsieskraal Rivers. Reports of the Cape Town City Engineer's Dept., namely Morrison (1982), Taljard (1984), Pitt (1987 and 1989) as well as the annual report of the City Engineer (1989) describe flow characteristics of the Black and Vygekraal Rivers as monitored over the past few years. Five reports compiled by consulting engineers Ninham Shand Inc. during the period 1979 to 1985 have documented flows in the canalized section of the Elsieskraal River. The only data found to describe stream sediment characteristics was an unpublished report by Willis (1979), although this was a geochemical study, rather than a sedimentological one. Computer-based literature searches were carried out for the author by a number of correspondents, but these could not find any further data.

1.1.2.2 Literature on background information

A large number of references were found describing the environmental elements of the study area. Previous research into the geology and soils within the catchment area of the Black/Vygekraal/Elsieskraal drainage system consisted of reports by: Smith-Baillie et al (1976), on soils of the Cape Peninsula; Rogers (1980), describing Cenozoic sediments of the Cape west coast; Hill and Theron (1981), in which the surface sand cover of Cape Flats was studied; Theron (1984), a booklet guide to the 1:50 000 Geological Survey map sheets representing Cape Town and its neighbouring areas; and Mountain et al (1990), a report on the engineering geology of Cape Town.

Papers published on the geology of this area include an overall description by Schwarz (1906); Mathias (1947), a study of the weathering products of Malmesbury Group shales; Kolbe (1966), on the geochemistry of the Cape Granites; a general description by Schalke (1973) of the Upper Quaternary sand cover of the Cape Flats; and Hartnady et al (1974), which summarizes the stratigraphy and structure of the Malmesbury Group of sediments in the south-western Cape.

Theses relevant to the study topic were: Westall (1961), on the petrology of Cape Granites; van der Merwe (1963), describing the geology of the northern Cape Peninsula; Galloway (1978), on the mineralogy of the Tygerberg Formation (in the Malmesbury Group); Christie (1981), a section of which deals with sediment provenance; King (1983), which studied the geomorphology of the Cape Peninsula; and du Toit (1984), a detailed granulometric study of the Cape Flats sand cover. Truswell (1977), describing the geological evolution of South Africa, was the only text found to be relevant to this section of the study. None of these studies, however, actually relate surface sand and soil cover to any sediments present in watercourses in the area.

The system devised by McHarg (1969), for mapping environmental sensitivity, was used as a basis for the description of the topography of the study area, in terms of the steepness of slope. All of the climatic data were obtained from the comprehensive survey of South African weather conditions by Schulze (1965). Mabbutt (1952) described earlier land use patterns in the Cape Town area, while the Cape Metropolitan Area Guide Plan (1988) summarizes land uses in the area, as in 1985. References which were of assistance in the classification and description of watercourses and catchment areas were: Strahler (1975); Cliff (1982); and Dardis et al (1988). A thesis by Rideout (1984) has researched the urban development history of Cape Town.

1.1.2.3 Literature in the field of sedimentology (theoretical, applied, case studies, and analytical techniques)

A number of sedimentology theory texts were of assistance in relating measured stream flows to potential sediment transport rates. These were: Blatt, Middleton and Murray (1972); Pettijohn (1975); Friedman and Sanders (1978); Leeder (1982); and Davis (1983). These references also gave some insight into interpretation of grain size distributions within sediments, in terms of indicating likely provenances. Selley (1988) and Lindholm (1987) are two modern texts which summarize known sedimentology theories, and apply them to the solution of various sedimentological problems. All of these references, however, deal with sedimentology on a general basis, and none of them include specific case studies relevant to the topic of this thesis.

Texts, dealing with fluvial dynamics and hydrology, rather than sedimentology, studied were: Crickmay (1974); Schumm (1977); Lewin (1981), and Shaw (1988). These references were of assistance in the understanding of the interactions between rivers and their environments, and they also provided guidelines on both river flow measurements and sampling of alluvial sediments. Numerous papers are available on the subject of sedimentology, some of them being individual case studies with a particular regard to the subjects of sediment provenance related to grain size analysis, and fluvial sediment transport, while others are more general research on the same topics.

Those dealing with provenance, researched by the author for this study, were the following: the important early study by Folk and Ward (1957), in which the significance of sediment grain size distribution parameters is assessed; a subsequent related study by Mason and Folk (1958) linking grain size analyses to the environments of sediment deposition; Friedman (1961), on the distinction between dune, beach and river sands based on their textural characteristics (which include grain size); Duane (1964), discussing the significance of skewness in recent sediments, with respect to provenance; Allen (1965), relating the characteristics of recent alluvial sediments to their origins; research by Visher (1969) on relationships between sediment grain size distributions and depositional processes; McLaren (1981), interpreting the meaning of trends in grain size measures; and Love et al (1987), on the sorting of sediments in fluvial systems.

Papers read, describing studies of fluvial sediment transport, were the following: Einstein and Johnson (1950), on the basic laws of sediment transportation; Allen (1965), relating the characteristics of recent alluvial sediments to their origins; two studies by Bagnold, on hydraulic sediment deposition (1968) and bedload transport (including saltation) (1973); Roberts and Pierce (1974), a case study into sediment transport and yields on a natural river system undergoing urbanisation; Shen (1978), a discussion of various sediment transport models; Banasik (1986), on sediment yield prediction from knowledge of catchment area soil loss; Bhowmik and Demissie (1986), a study of wetland sediment-water interactions; Christiansen (1986), describing measurement of suspended sediments in an estuarine setting;

Mantz and Emmett (1986), a comparison of sediment transport in different streams within the same region; Renger (1986), on continuous river sediment concentration measurement; Rooseboom (1986), relating sediment transport to stream power; Westrich (1986), a hydromechanic study of fluvial sediment transport; Best (1987), relating flow dynamics at river confluences to sediment transport; and Reid and Frostick (1987), describing further research into bedload transport in rivers. Although few of these references were directly related to the actual study topics of this thesis, a number of them did discuss research undertaken on similar fluvial systems, while others indicated which analytical techniques might produce the most meaningful results in terms of determining the provenance of the sediments.

References found to be of assistance, regarding the analytical techniques used, were: texts by Carver (1971), on general sedimentary petrology and related analytical procedures, and Carroll (1970), a guide to the X-ray diffraction of clay minerals. Hawker (1986), an M.Sc. thesis, was a useful pointer as to the separation of the gravel, sand, silt and clay fractions of the sediments. Flemming and Thum (1978), and Brink and Rogers (1985), set out the particle size analysis procedures which were followed in this section of the research. Beal and Sheppard (1956), applied the system devised by Powers (1953), for the description of grain roundness. Krinsley and Doornkamp (1973) used the surface textures of quartz sand grains to suggest their likely origins. This reference, however, is basically related to the use of scanning electron microscopy, and is thus only likely to be of use in possible further studies of the alluvial material within the study area. The same applies to the paper by Hatherly and Viewing (1982), which suggests geochemical methods that might be used in the determination of sediment provenance.

1.1.2.4 Literature on statistical techniques

The user's manuals for the SAS and BMDP statistical software packages (1985 and 1988 respectively) were used as general guides in the application of statistical methods to the interpretation of the sediment samples characteristics data, as well as in the writing of particular programmes. The text by Johnston (1978) was also found to be a useful supplementary guide in this regard. Particular case studies by Macdonald (1984), on the statistical distinction between formations within the Ecca Group on the basis of their radioactive signatures, and by Holmes (1987), on the statistical separation of soil units in the north-east Cape, were used as guides in the application of multivariate techniques to the data set.

1.1.2.5 Literature on rock weathering and soil erosion

Texts by Merrill (1906) and Ollier (1969), on rock weathering and subsequent soil erosion, were of use in giving the author a more complete understanding of these processes, while Baver et al (1972) gave a detailed insight into the causes and results of soil erosion, which can supply sediment to river systems. Brown (1950) discussed the effects of soil conservation. Theses by Boddington (1980), Hudson (1987), and Hallward (1988) all deal with the problem of soil erosion, and discuss the application of the SLEMSA model proposed by Ellwell (1977) to various differing environments. A paper by le Roux (1990) discusses rates of fluvial erosion and sediment production throughout South Africa, while another by Liu et al (1990) investigates ways of preventing or alleviating wind-induced soil erosion by means of vegetative arrays. The SARRCUS (1981) system has been referred to regarding the classification of different types of soil erosion in South Africa.

1.1.2.6 Literature on river management

Four papers were read which deal with this subject. Beaumont (1986) discusses the overall management of water in the environment; Anderson (1989) describes planning procedures followed in Australia; Wiseman (1990) summarizes stormwater management and land use planning in river systems in the south-west Cape; while Ferguson (1990) considers various aspects of stormwater management.

1.2 HYPOTHESIS

Soil erosion within the catchment areas of the Black, Vygekraal and Elsieskraal Rivers is followed first by transport, and then by deposition of this eroded material downstream, in the lower reaches of the Black and Vygekraal Rivers between Athlone and Observatory (the so-called "dredged area" referred to in section 1.1.1). A rapid decrease in the stream gradient, and therefore a resultant reduction in the flow velocity of the river system, in this vicinity, is responsible for the deposition of the sediments.

Topsoil and sand cover in these catchment areas is mobilized by rain and subsequent overland flow during the wet winter months (especially June, July and August), and by the strong, persistent southerly winds which blow throughout most of the summer period (particularly during December, January and February). This eroded material, transported by overland flow and/or wind, then enters the river systems (much of which are canalized) either directly, or via the culverts of the stormwater drainage systems.

For the purposes of this study, the catchments of the Black, Vygekraal and Elsieskraal Rivers will be regarded as three distinct areas (Figure 2), each contributing a certain amount of sediment to the total load received by the dredged area. The amount of sediment delivered by each of the three catchments should be dependent on (firstly) the amount of material supplied by each area, and (secondly) the ability of the rivers/canals within each area to transport this sediment to the dredged area.

The unconsolidated sand cover, which is prevalent over virtually the entire catchment area of the Vygekraal River (on the Cape Flats) is, owing to its mainly medium-grained size distribution, very easily mobilized and transported by both wind (Hallward, 1988) and moving water (Bagnold, 1968). This situation is aggravated by the lack of vegetative cover in this area, and furthermore by people walking and cars being parked on the sparsely vegetated or bare sidewalks.

In the upper part of the Elsieskraal River's catchment area, the typically loamy topsoil, produced by mechanical and chemical weathering of the shales of the underlying Malmesbury Group strata, is less susceptible to erosion than are the sands of the Cape Flats. This is due to the presence of clays within the soils, which result in their sand grains being held together by the cohesive character of the clays. Steep slopes on the Tygerberg Hills, however, are a cause of soil erosion in this area. The lower part of the Elsieskraal catchment is more similar to the Vygekraal catchment, typified by an unconsolidated sand cover on mainly flat ground. The catchment area of the Black River is the least vulnerable to soil erosion, since very little loose sand cover is present in the area, owing to its well-vegetated sidewalks, gardens and open spaces, and slight gradients.

Regarding the transporting ability of each of the three major rivers, it appears that the best method of estimating this would be to use the applied stream power approach suggested by Rooseboom (1986). This sediment transporting power will be dependent on both stream discharge (Einstein and Johnson, 1950; Bhowmik and Demissie, 1986), and shear (bed) flow velocity (Bagnold, 1973; Leeder, 1982). From these considerations, it seems likely that the Vygekraal River has the greatest potential to transport sediment, while the Black River has the least. This aspect is discussed in detail in Chapters 3 and 6.

Combining the sediment supply with the stream power, it is probable that the major contribution to the sediments deposited in the dredged area comes from the Cape Flats area via the Vygekraal River, with an intermediate quantity of material being transported by the Elsieskraal River, and a minor amount of sediment being derived from the catchment area of the Black River. Most of the sand delivered by the Vygekraal River is deposited in the upper half of the dredged area, whereas the fine-grained sediments (silt and clay) originating from the Tygerberg Hills area and transported by the Elsieskraal River, can still be carried by the slow-flowing waters of the lower Black/Vygekraal channel, and are thus deposited further downstream in the extreme lower section of the dredged area.

1.3 AIMS AND OBJECTIVES OF THE STUDY

1.3.1 Aims of the study

This thesis is a pilot study which addresses the problem of soil erosion within the study area, and the resultant transportation and deposition of sediment in the lower reaches of the Black and Vygekraal Rivers. The conclusions drawn will be semi-quantitative, and all recommendations should be regarded as preliminary.

i. The primary aim of this study is to determine, as far as is possible, the proportional (or percentage) contribution of each of the three main sub-catchments within the study area, i.e., those of the Black, Vygekraal and Elsieskraal Rivers, to the total sediment load which is transported annually to, and deposited in, the "dredged area" referred to in sections 1.1 and 1.2. These relative sediment contributions of each of the three rivers are represented as estimates of sediment yield from each of the three sub-catchments.

ii. A secondary (more minor) aim of the study is to identify possible sites of soil erosion within these three sub-catchment areas, and to provide preliminary ideas on ways of modifying land use patterns and management practices in order to minimise the presently observed sand and soil loss at these particular localities.

1.3.2 Objectives

The objectives of this study, which are seen as leading toward its final aims, are:

i. A description, and comparison, of the three major sub-catchment areas (Black, Vygekraal, Elsieskraal), since these tracts of land are the source areas for the sediments which are transported to the dredged area.

ii. The calculation of the relative transporting powers of the Black, Vygekraal and Elsieskraal Rivers within their sub-catchments.

iii. A description, and comparison, of the sediment samples taken from the three sub-catchment areas and the dredged area. Characteristics considered will be: particle (grain) size distribution, grain shape, and mineralogy and material type.

iv. A statistical analysis of the grain size distributions of the sediment samples from the three sub-catchments and the dredged area.

1.4 STUDY PLAN

1.4.1 Explanation and justification of approach

The study area was divided into three sub-catchments. A more detailed division of the area would have resulted in a sample collection programme (followed by the necessary analytical procedures and research) too lengthy and complex to have been adequately completed within the available time span.

A representative set of stream sediment samples, if grouped in terms of catchment areas and dredged area, should display trends in grain size and mineralogy/material type. These trends are likely to have some degree of significance in the determination of the provenance of the sediments in the dredged area, since the final properties of a sedimentary deposit are strongly influenced by those of the source material. These inherited properties should be particularly diagnostic of sediment provenance where two (or more) source areas contain materials which are unique to each area. This is the case when comparing the surface cover in the upper Elsieskraal catchment (mainly loamy soils) to that in the catchment of the Vygekraal River (unconsolidated silica sand). The distinction between the surface cover materials of the catchments of the Black and Vygekraal Rivers is, however, not so clear cut, since the Black River catchment is also covered mostly by silica sands.

The statistical analyses should assist further in highlighting inherent differences (and also similarities) between the sediments of the three sub-catchments and those of the dredged area. This might be able to shed some further light on the question of the provenance of the sediments in the dredged area. Owing to time constraints, possible legal difficulties, and the large size of the study area, methods using either radioactive tracers or stable isotope tracers to determine sediment provenance were considered impractical, and thus were not considered as research methods for this particular study. Such techniques could be employed in any research which might be undertaken as a sequel to this study. Geochemical investigations could also be carried out on stream sediments (particularly with respect to major and trace element analyses), and also on suspected source material, in order to verify the findings of this study.

1.4.2 Methodologies

Methodologies to be followed in the analytical part of the research are, in order of presentation in the text:

i. Watercourse flow measurements, in order to estimate the relative potential sediment transporting powers of the Black, Vygekraal and Elsieskraal Rivers. Discharges of these watercourses were calculated from flow velocity readings, while shear (bed) velocities were calculated from available data, using theoretical formulae.

ii. Stream sediment samples were first analysed in order to determine their proportions of gravel, sand, and fine materials. This was done by means of dry sieving, deflocculation, wet sieving, oven-drying, and weighing of retained fractions. In addition, organic matter content was determined by treating with hydrogen peroxide.

iii. The fine fractions (silt and clay) of those samples containing such material, were analysed for particle size distribution on a sedigraph analyser. This procedure also determined the silt:clay ratios within the fine fractions.

iv. The sand fractions of the samples were analysed for particle size distribution in a settling tube. As with the sedigraph, this procedure was able to calculate the mean size, median size, sorting, skewness and kurtosis of the samples. Modal sizes were estimated by examination of the graphical printouts derived from the programme.

v. The clay fractions of the samples, obtained by agitation of the fine fractions followed by settling out of the silt component, were analysed by X-ray diffraction, in order to determine (qualitatively only) their mineralogy.

vi. The modal sand fractions of the samples were studied under a low-powered microscope, so as to perform grain counts on the samples (with respect to mineralogy and/or material type), and also to examine grain shape.

vii. Various computer-based statistical programmes were run on the data set obtained from the particle size analyses. These included both univariate and multivariate tests from the SAS and BMDP packages. Programmes

CHAPTER 2 : DESCRIPTION OF STUDY AREA

Sediment discharge (transport) of river systems is largely influenced by various factors within their catchment areas. These factors are: bedrock geology, soil cover, relief (altitude differences and slope steepness), climate (wind and precipitation), and vegetative cover (largely determined by land use patterns). These characteristics are therefore discussed, with reference to the study area, in sections 2.2, 2.3, 2.4 and 2.5.

2.1 LOCATION, SIZE AND URBAN DEVELOPMENT HISTORY OF STUDY AREA

The study area consists of the catchments of the Black, Vygekraal and Elsieskraal Rivers, a total area of 169,65 km². Of this, the largest proportion is covered by the catchment area of the Elsieskraal River, namely 86,84 km². The Vygekraal River's catchment area is 66,91 km² in extent, while that of the Black River covers only 15,90 km². This tract of land extends from Kenilworth in the far south-west to Durbanville in the extreme north-east, while the south-eastern and north-western limits can be taken as Nyanga and Maitland respectively (Figure 2).

The majority of land within this study area has undergone urbanization, as a result of the spread of the suburbs of Cape Town. In 1860, the railway lines to Stellenbosch, Paarl, and Muizenberg were constructed, in conjunction with the main roads adjacent to them. This initiated the two ribbons of commercial development which today form Cape Town's "northern suburbs" and "southern suburbs", established during the residential occupation following the commercial development (Rideout, 1984).

Later, mostly during the early parts of this century, suburban development also spread to the less attractive Cape Flats region, where lower income housing has become dominant. Formerly outlying rural villages such as Durbanville have since also been incorporated into the ever-expanding urban sprawl. The "northern suburbs", however, are in fact separate municipalities, namely Pinelands, Goodwood, Parow, Bellville and Durbanville.

2.2 GEOLOGY OF STUDY AREA

The calculation of areas of surface cover of the various geological units within the study area has been based on the information contained on the 1:50 000 geological sheet maps for Cape Town and environs. The figures presented in this section of the study therefore are likely to represent the original, natural geological surface cover or outcrop. Although this pattern has probably been altered in some parts of the study area as a result of urbanization, the basic distribution patterns of units such as the Quaternary Cape Flats sand and the Malmesbury Group-derived loam soils of the Tygerberg Hills have not been significantly changed. Owing to their geographical distribution, these two distinct units should have a marked influence on the sediments carried by the Vygekraal and Elsieskraal Rivers.

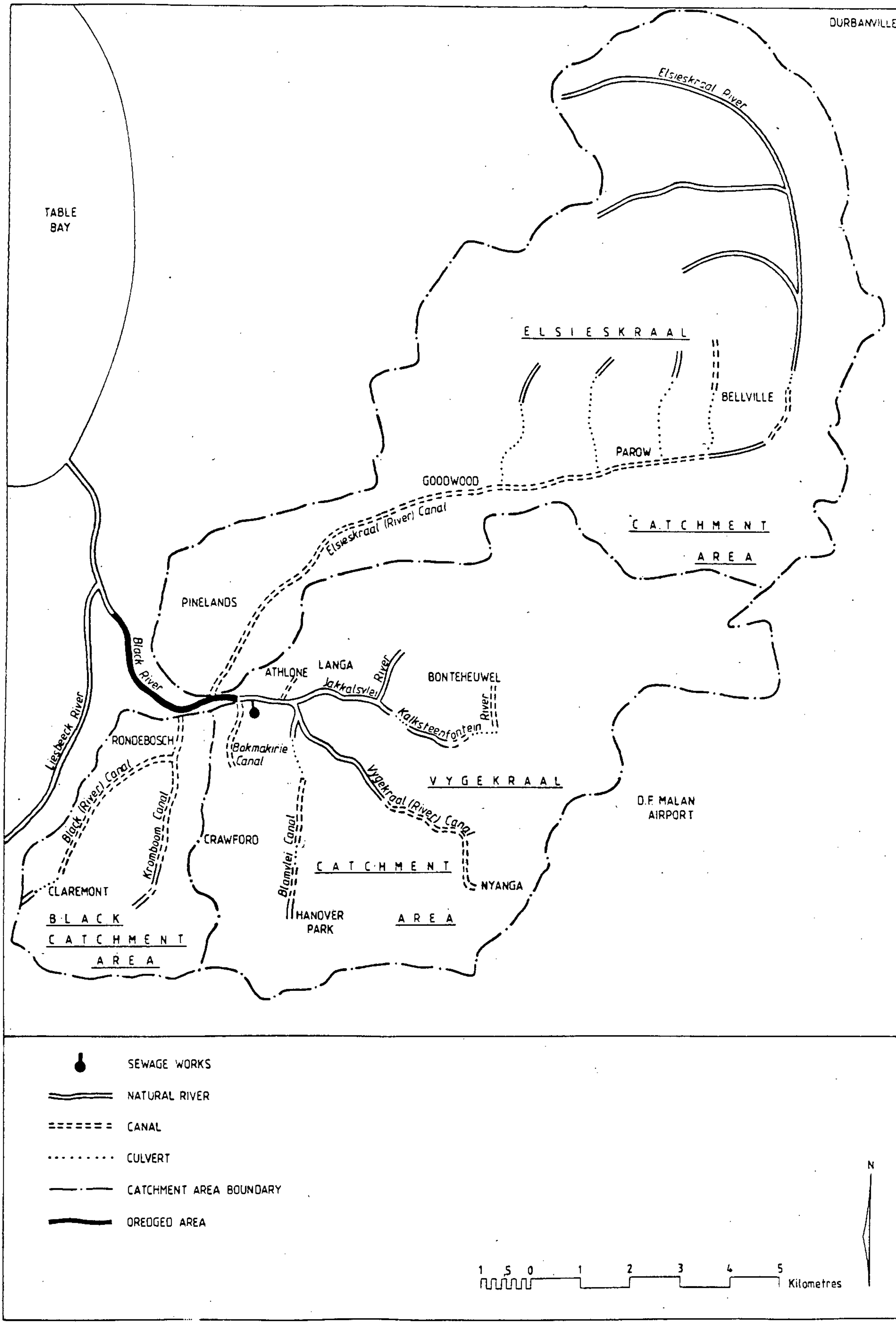


Figure 2 : Study Area - Subdivision into the Black, Elsieskraal and Vygekraal catchment areas

2.2.1 Rocks

2.2.1.1 Malmesbury Group

The strata of the Malmesbury Group are the oldest rocks either underlying, or outcropping in, the study area. The Tygerberg Formation is the only unit of Malmesbury strata present within the study area, and its age has been estimated at between 610 and 505 million years (Truswell, 1977). The rocks normally referred to as the "Malmesbury shales" are, in fact, a fairly complex assemblage of alternating beds of fine-grained pelitic shale, semi-pelitic siltstone and fine-grained greywackes (Galloway, 1978). The pelitic shales are extremely fine-grained, with an average grain size of less 4 ϕ (0,0625 mm), whereas the greywackes are fine to medium-grained, with grain sizes ranging from 3 ϕ (0,125 mm) to 2 ϕ (0,25 mm) (Westall, 1961).

At many places, these sediments have undergone low-grade metamorphism of the greenschist facies, and this has resulted in the affected strata being altered to hornfels, slate and immature quartzite. This metamorphism, and associated folding, are likely to have been related to the intrusion of the Malmesbury strata by the Cape Granites (Truswell, 1977). The pelitic sediments contain, apart from quartz, feldspars (both plagioclase and potassium feldspar), haematite and muscovite, as well as felted masses of sericite, biotite and chlorite, whereas the greywackes normally contain approximately 50 % quartz, 10 % feldspar (usually plagioclase), and a micaceous matrix (Galloway, 1978). Extensive cordierite spotting occurs in the metamorphosed sediments (Hartnady et al, 1974). The Tygerberg Formation is frequently deeply weathered to clays (Theron, 1984), which consist mainly of kaolinite and halloysite (Mathias, 1947). Iron oxides are also often present in weathered material derived from these rocks. The feldspars in the greywackes weather rapidly to kaolinite, muscovite and biotite (Westall, 1961; Galloway, 1978). This weathered Malmesbury material may be transported directly, mainly as clays, into the Elsieskraal River's drainage system, or it can become a component of the loamy soils in this area. The heavy mineral assemblage present in the Tygerberg Formation consists of tourmaline, apatite, zircon, magnetite and pyrite.

Within the study area, the Tygerberg Formation outcrops almost exclusively in the upper parts of the Elsieskraal River's catchment area, on the slopes of the Tygerberg Hills north of Bellville (Figure 3). These outcrops cover an area of 14,68 km² (Table 1). A very small outcrop, of area 0,21 km², occurs in the Newlands area adjacent to the Black River canal. The Tygerberg Formation underlies most of the study area, at depths varying from 0 m to 30 m (Theron, 1984).

2.2.1.2 Cape Granite Suite

The Cape Granites, in the vicinity of Cape Town, comprise two distinct plutons, namely the Cape Peninsula Pluton, which outcrops only in the extreme south-west of the Black River's catchment area, on Wynberg Hill (area 1,23 km²), and the Kuils River-Helderberg Pluton, which outcrops in limited extent (area 0,45 km²) on the eastern slopes of the Tygerberg Hills (Figure 3). These granitic intrusions also underlie areas immediately adjacent to their outcrop. The age of the granites is thought to be approximately 500 million years (Truswell, 1977).

TABLE 1 : ORIGINAL GEOLOGICAL SURFACE COVER AND OUTCROP IN STUDY AREA

Type of cover	Age	Group/ suite	Formation/ pluton	Lithology	Percentage cover in catchment area		
					Black	Vygekraal	Elsieskraal
mainly unconsolidated sediments	Quaternary	unnamed	Bredasdorp Formation	calcareous sand	0,00	16,34	0,82
				high-grade silica sand	47,80	45,37	11,00
				low-grade silica sand	43,14	38,29	51,46
			unnamed	sandy loam	0,00	0,00	17,04
				silcrete/ ferricrete	0,00	0,00	2,03
rock outcrop	Jurassic	unnamed	unnamed	dolerite dykes	0,00	0,00	0,22
rock outcrop	Cambrian	Cape Granite	Cape Peninsula	coarse porphyritic granite	7,74	0,00	0,00
			Kuilsriver-Helderberg	coarse porphyritic granite	0,00	0,00	0,52
rock outcrop	Namibian	Malmesbury	Tygerberg	phyllite	1,32	0,00	10,00
				fine-grained greywacke	0,00	0,00	6,91

Note: Areas calculated from 1984 1:50 000 geological sheet maps for Cape Town (3318CD) and Bellville (3318DC)

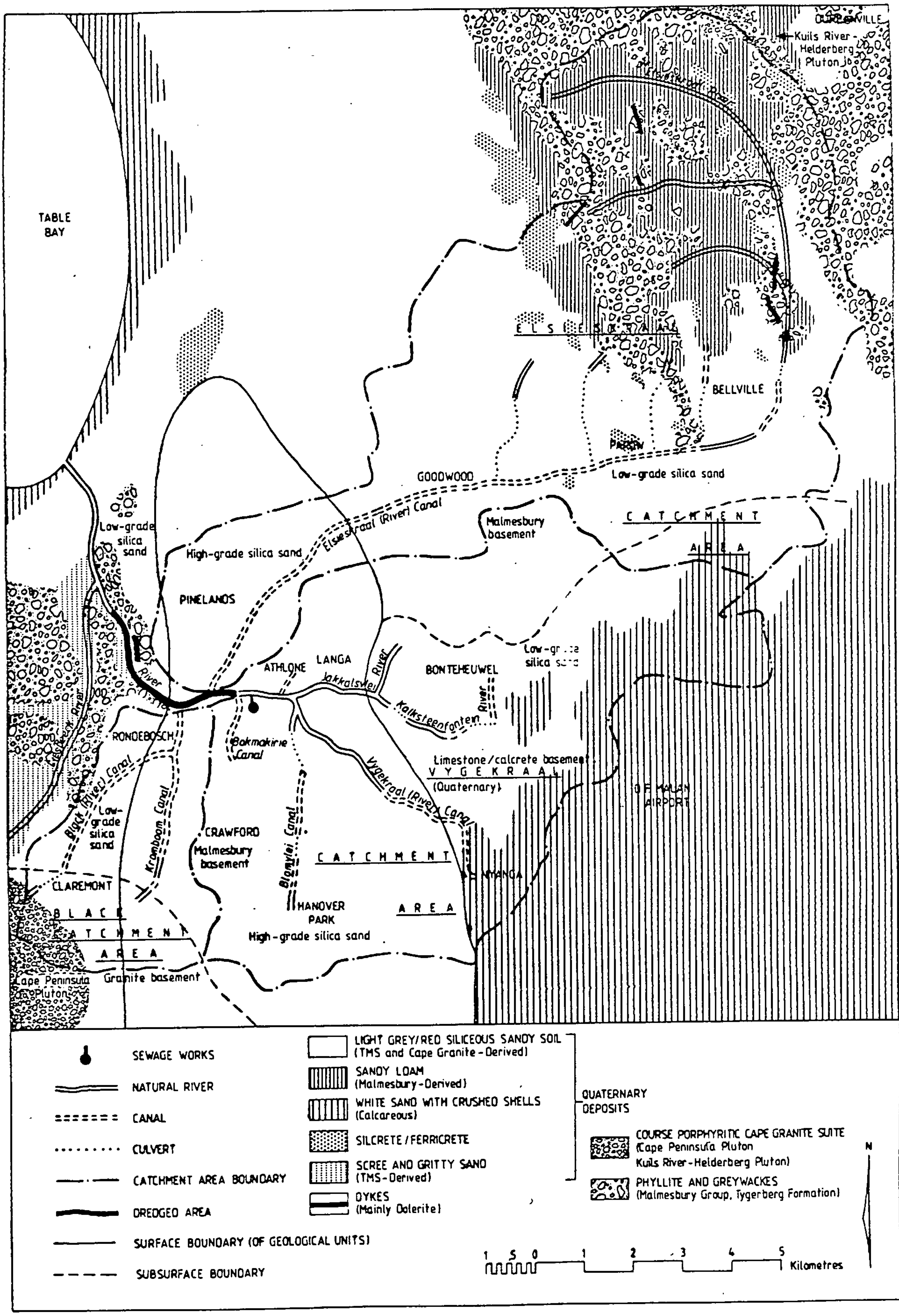


Figure 3 : Geology of study area

The mineralogy of both plutons is virtually identical, with both typically consisting of a coarse porphyritic granite (van der Merwe, 1963), which normally contains large microcline feldspar phenocrysts set within a medium-grained matrix of quartz, various feldspars, muscovite and biotite. Heavy minerals most commonly present are tourmaline and zircon. According to Kolbe (1966), an average modal mineral analysis for Cape Granites comprises: 28 % quartz, 28 % microcline feldspar, 28 % plagioclase feldspar, 10 % biotite, 4 % muscovite, and 2 % heavy minerals. Similar values are given by Westall (1961), and van der Merwe (1963). Weathering products of the granites consist of both quartz sands derived from the mechanical abrasion of their quartz components, and clays produced from the chemical breakdown of feldspars and micas (Ollier, 1969). However, owing to the limited extent of granite outcrop in the study area, such weathering products are not believed to constitute a significant proportion of the sediments transported by any of the rivers.

2.2.1.3 Table Mountain Group

Although the sandstones and quartzites of the Table Mountain Group do not occur anywhere within the study area, they are believed by most geologists to have provided the majority of the source material for the quaternary sand deposits which presently cover the Cape Flats area (Hill and Theron, 1981). Table Mountain Group sediments are estimated to be of an age ranging between 500 million years and 400 million years (Truswell, 1977; Theron, 1984). They consist of medium to coarse-grained ($2\ \phi$ to $0\ \phi$) quartzitic sandstones which may contain subordinate conglomerate lenses and vein quartz. In previous geological times, Table Mountain Group sediments overlaid the Malmesbury basement of the Cape Flats area. Folding resulted in the formation of an anticline over the Cape Flats (King, 1983), which was subsequently removed by erosion (Schwarz, 1906). No further accumulation of sediments occurred on the Cape Flats, until the production, during Quaternary times, of the present-day sand cover.

2.2.1.4 Other intrusives

In addition to the Cape Granites, there are very limited occurrences of other intrusive rocks within the study area. These take the form of dolerite dykes, younger in age than the Table Mountain sediments, i.e., the dykes vary in age from 380 million years to 190 million years (Theron, 1984). Their only outcrop is in the Tygerberg Hills vicinity, and is just 0,22 km² in extent (Table 1). Owing to this very small outcrop area, these exposures do not contribute a significant amount of material toward the load carried by the Elsieskraal River.

2.2.2 **Unconsolidated sand**

2.2.2.1 Silica sand

The silica (quartz) sands which cover the Cape Flats region are thought to be the major natually occurring source material for the sediments transported by the Black, Vygekraal and Elsieskraal Rivers. In the cases of the Black and Vygekraal Rivers, these sands are likely to be the sole natural source for their alluvial material. It is possible, however, that in the south-west of the Black River catchment (on Wynberg Hill), there might be mixing of granite-derived soils with the silica sands by aeolian means (Smith-Baillie et al, 1976), but the extent of this is rather uncertain. The silica sand cover extends over 55,98 km² (83,66 %) of the catchment area of the Vygekraal River. Within the catchments of the Black and Eisieskraal Rivers, the sands cover 14,46 km² (90,94 %) and 54,25 km² (62,46 %) respectively (Figure 3;

Table 1). The sand cover varies in thickness from 5 m to 40 m (Rogers, 1980), being thickest where depressions exist in the Malmesbury basement.

According to Hill and Theron (1981), the likely major source for these silica sands was the arenaceous Table Mountain Group. Weathering of the Table Mountain quartzites produced quartz sands which were further reworked by fluviatile, aeolian and marine agents (Mabbutt, 1952) after deposition on the Malmesbury basement of the Cape Flats during the Quaternary period, i.e., within the last 1,8 million years. Rogers (1980) suggests that the Cape Granites might also have provided some source material for the silica sands, although this is likely to have been in much smaller quantities than that derived from the Table Mountain quartzites. Any feldspathic material from the granites would have been altered to clays and micas during transport (Christie, 1981), and it is unlikely that such material would be incorporated in the sands, bearing in mind the forces of reworking.

Hill and Theron (1981) describe two distinct categories within the silica sands, based on the suitability of the sands for glass manufacturing. A "high grade" sand, possessing an extremely high quartz content (exceeding 98 %), covers the western half of the Vygekraal catchment area, the eastern half of the Black catchment area, and the south-western extremity of the Elsieskraal catchment area (Figure 3). A "low grade" sand, having a lower quartz content (between 90 % and 98 %), and containing more impurities, covers most of the remainder of the Vygekraal and Black catchment areas, and the central parts of the Elsieskraal catchment area. Rogers (1980) has attempted a tentative stratigraphical classification of these deposits: the unconsolidated deposits, generally, belong to the Bredasdorp Formation, with the low grade sands comprising the Epping Member, and the high grade sands the slightly younger Philippi Member, which may in places overlie the Epping Member of these sand deposits.

The uppermost 5 m of the Cape Flats silica sands are usually moderately well sorted and medium-grained, i.e., grain sizes generally range from 2 ϕ (0,25 mm) to 1 ϕ (0,5 mm). These surface sediments are often slightly negatively skewed (with respect to their particle size distribution) as a result of winnowing of very fine sand from the deposits by wind action (du Toit, 1984). Below depths of 5 m, sorting becomes poorer, mud content increases, and the sand itself becomes coarser (Rogers, 1980). For the purposes of this study, however, only the surface deposits will be considered, since sands at depths exceeding a few metres are unlikely to be affected by the agents of erosion in an area of low relief such as the Cape Flats (Schalke, 1973). In these surface sands, clay minerals are negligible (Hill and Theron, 1981). Heavy minerals (which normally constitute tourmaline, zircon, apatite, pyrite and iron oxides) rarely comprise more than 0,2 % of the naturally occurring sand deposit. In some areas, mainly toward the east and south-east, calcium and aluminium oxides may constitute as much as 2 % of the sands, but elsewhere they are negligible. The surface silica sands are typically light grey in colour (10YR 7/1 to 10YR 7/2, according to the system of Munsell, 1975).

2.2.2.2 *Calcareous sand*

Sand containing significant amounts of calcium carbonate is referred to by Theron (1984) as "shell-bearing dune sand". It is thought to be of a younger age than the silica sands, and is likely to have been blown from the False Bay beaches by the southerly winds which are dominant during the summer months. Its grain size and sorting are more variable than those of the silica sands, due mainly to the mixing of finely crushed shells with quartz grains. Some degree of gradation and interfingering between the calcareous sands and the silica sands does occur in the south-eastern sector of the Vygekraal River's catchment area, where the calcareous sands cover an area of 10,93 km^2 (Figure 3). A small, contiguous area of 0,71 km^2

is covered by the calcareous sands in the far south-east of the Elsieskraal River's catchment. The calcareous sands probably only contribute a minor proportion to the total sediment load of the Vygekraal River drainage system, and their quartz component is unlikely to be easily distinguished from the actual silica sands. These deposits have been provisionally classified by Rogers (1980) as belonging to the Wolfgat Member of the Bredasdorp Formation.

2.2.3 Soils

2.2.3.1 Loam

A large part (17,04 km^2) of the Tygerberg Hills area is thinly covered by sandy clay loam soils of the truncated podsolic type (Mathias, 1947), which are essentially derived from weathering products of the Malmesbury Group sediments. These soils are poorly sorted, and often contain fragments of vein quartz, as well as small nodules of ferricrete (Theron, 1984). Generally, the colour of these soils ranges from light brownish grey (10YR 6/2) to pale yellow (2,5Y 7/4) (according to the system of Munsell, 1975). The mass proportions of their components are: 5 % to 40 % clay (mean 24 %); 5 % to 50 % silt (mean 26 %); 30 % to 90 % sand (mean 49 %); and gravel (mean 1 %). The sand component of these soils is usually fine- to medium-grained (3 ϕ to 1 ϕ). The loam either directly overlies the Malmesbury basement, or it grades into a clay layer, which in turn rests upon the Malmesbury bedrock.

Quartz grains are the dominant constituent of the sand fraction, which may also include fragments of weathered Malmesbury bedrock. Aggregates of clay-size grains may also appear to belong to the sand fraction (on the interpretation of sieve analysis results). The most common clay minerals in these soils are kaolinite and halloysite (Mathias, 1947), while the presence of montmorillonite and illite is uncertain. The clays are derived from the chemical breakdown of feldspars and micas (Merrill, 1906; Ollier, 1969). High biotite contents in some of the Malmesbury bedrock has resulted in these soils often possessing high iron oxide contents, which should, in turn, be reflected in the sediments transported by the Elsieskraal River. This is, in fact, vindicated by research carried out by Willis (1979), which showed Elsieskraal River alluvium to have a significantly higher iron content than sediments carried by either the Black or Vygekraal Rivers (the alluvial material transported by the Vygekraal River showed a particularly low iron content). Heavy minerals present are zircon, tourmaline, epidote and rutile. The loam soils normally have a low organic matter content. These soils probably provide most of the naturally occuring material that is transported by streams in the upper part of the Elsieskraal River's catchment area. Ultimately, therefore, this material must form a significant proportion of the entire sediment load delivered by the Elsieskraal River to the dredged area.

2.2.3.2 Silcrete/ferricrete

These deposits, of Quaternary age, are of very limited extent (1,76 km^2), and occur only in the Elsieskraal catchment, mainly on the southern and western slopes of the Tygerberg Hills (Figure 3). They consist of a number of small, isolated patches which rest on Malmesbury bedrock, and have been formed by groundwater concentration of either silica of iron oxide derived from the underlying weathered bedrock (Theron, 1984). Silcrete usually consists of a hard, silicified deposit of various grain sizes, which may contain vein quartz pebbles and clay lenses. Ferricrete normally comprises an amorphous mass of ferruginized nodules, sand and clay cemented by iron oxide (Theron, 1984). It is, however, unlikely that these deposits contribute a significant amount of material to the sediment load transported by the Elsieskraal River.

2.3 TOPOGRAPHY OF STUDY AREA

The topographical features of the study area may be broadly divided into two major areas: a generally flat region (the Cape Flats), extending over the entire catchment areas of the Black and Vygekraal Rivers, and over the southern parts of the Elsieskraal catchment; and a zone of higher relief and steeper slopes which comprises the Tygerberg Hills and their immediate vicinity, occupying the northern parts of the Elsieskraal catchment (Figure 4).

This is, however, a simplification. The Cape Flats sector of the study area, extending from Kenilworth in the south-west to Bellville in the north-east, is not entirely devoid of any relief. There are small, isolated areas in Rondebosch, Newlands, Claremont and Kenilworth where slopes do exceed 2,5 %, and on Wynberg Hill, slopes may be as much as 10 % to 25 %. At least half of the area covered by the catchment of the Black River is, however, characterised by slopes of less than 2,5 %.

Of the three catchments within the study area, that of the Vygekraal River is the flattest. Here, approximately half of the terrain has a slope of less than 1 %, while slopes of 2,5 % are rarely exceeded in the remainder of the catchment. Only toward the eastern boundary of the Vygekraal catchment do slopes exceeding 2,5 % occur, and these are only on the flanks on isolated dune ridges. These dune ridges are rarely higher than 10 m (with respect to the surrounding land), and are oriented in a north-south direction, since their formation has been controlled by the southerly winds which blow during the dry summer months and are responsible for the aeolian transport of sand. The dune ridges extend inland from False Bay, and are separated by depressions (Mabbutt, 1952).

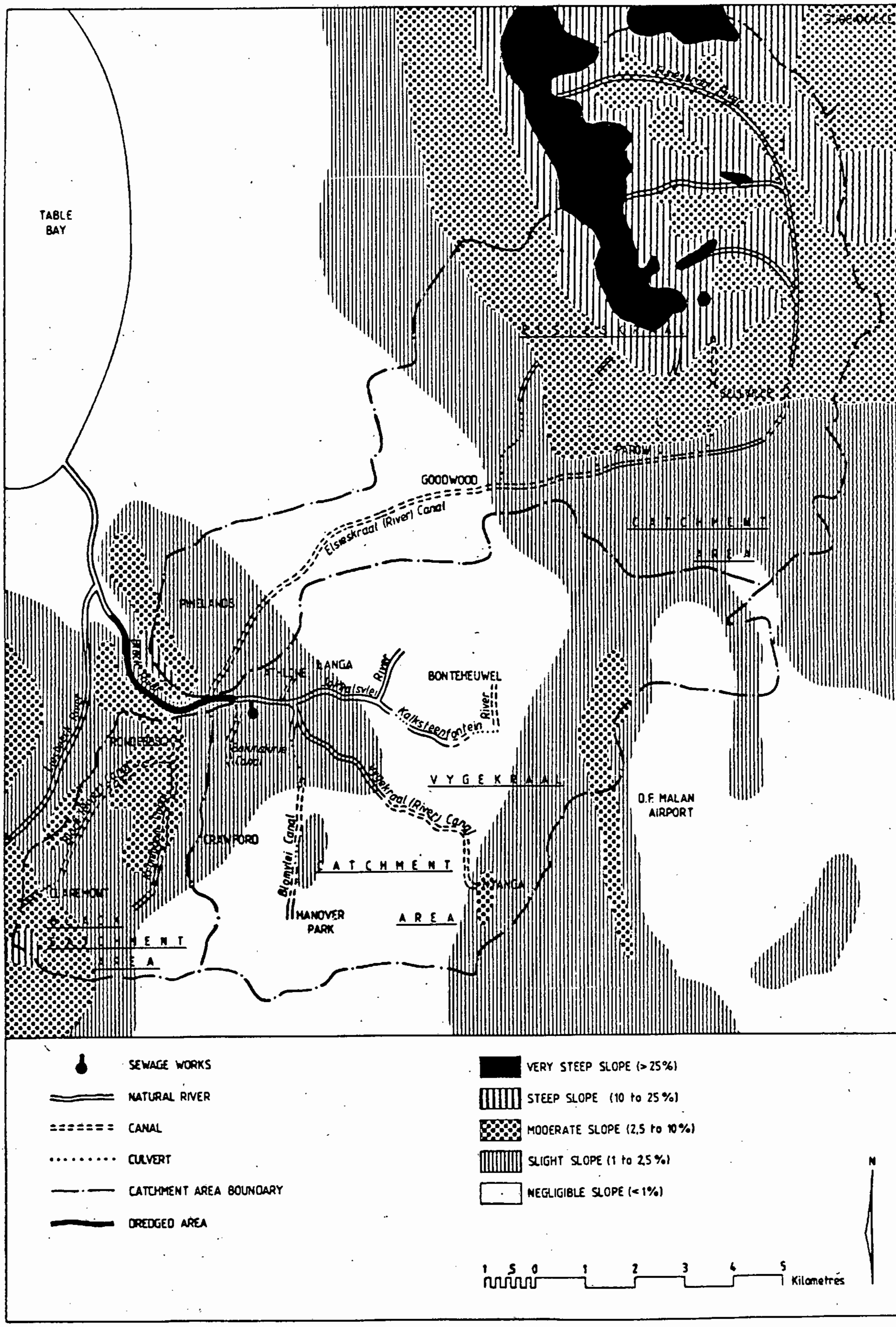


Figure 4 : Topography (slope) of study area

The catchment of the Elsieskraal River has both the steepest slopes, and the highest relief, to be found within the study area. These topographical features take the form of a range of rounded hills (the Tygerberg), situated to the north and north-west of Bellville. The Tygerberg Hills attain an elevation of some 400 m above the flat, low-lying land to their west and south, with slopes on the steepest parts of their flanks generally exceeding 25 %. To the immediate east and north-east of the Tygerberg is an undulating area of moderate relief, within which the Elsieskraal River gathers its headwaters (Figure 4). Slopes in this region, within which the settlements of Durbanville, Kenridge and Welgemoed have been established, vary from 2,5 % to 25 %. The low-lying land in the Bellville South/Parow/Goodwood/Pinelands area generally has slopes of less than 2,5 %. Only in the extreme south-west, on the western boundary of Pinelands adjacent to the dredged area, is there any relief, this being a low ridge some 10 m to 15 m in height, with slopes in the order of 10 %.

A classification of slope percentage in terms of land susceptibility to soil erosion, based on the system devised by McHarg (1969), is also shown on Figure 4. While this method is a simplification of the relationship which exists between slope steepness and severity of soil erosion, it is likely to hold true for many areas, particularly those where land is either in its natural (vacant) state, or under agriculture. Steeper slopes also give rise to faster flowing streams, which in turn have greater sediment transporting power. It is thus probable that slope-induced soil erosion and sediment transport is most common (and of greatest magnitude) in the Tygerberg Hills region, and relatively insignificant elsewhere within the study area.

2.4 CLIMATE OF STUDY AREA

The Cape Town region has a mediterranean climate, characterised by warm, dry summers and cool, wet winters. Strong winds are a notable feature of the climate throughout the year, particularly during the summer. All of the data presented in this section have been summarized from Schulze (1965), and they refer to measurements taken over a number of years at D.F. Malan Airport. Since the airport is situated on the Cape Flats, on the eastern edge of the Vygekraal River's catchment area, it may be considered to be a representative station for the climate of the study area, except, perhaps, with respect to rainfall.

2.4.1 Temperature

The study area experiences moderate annual and daily ranges of temperature, since it is subject to the maritime influences of the surrounding ocean (the Atlantic and False Bay). Daily mean average temperatures vary from 12°C in July, to 21°C in February (Figure 5). Mean daily maxima range from 17°C in July, to 27°C in February. The corresponding figures for mean daily minima are 7°C and 15°C. Temperatures exceeding 40°C, or lower than 0°C, have been recorded, but rarely occur.

2.4.2 Rainfall

The mean annual rainfall recorded at D.F. Malan Airport over a number of years is 625 mm. The wettest month is June (105 mm), while the driest is February (10 mm) (Figure 6). During the wet winter period, 12 to 15 rainy days may be expected each month, with this figure decreasing to 4 rainy days per month during the summer.

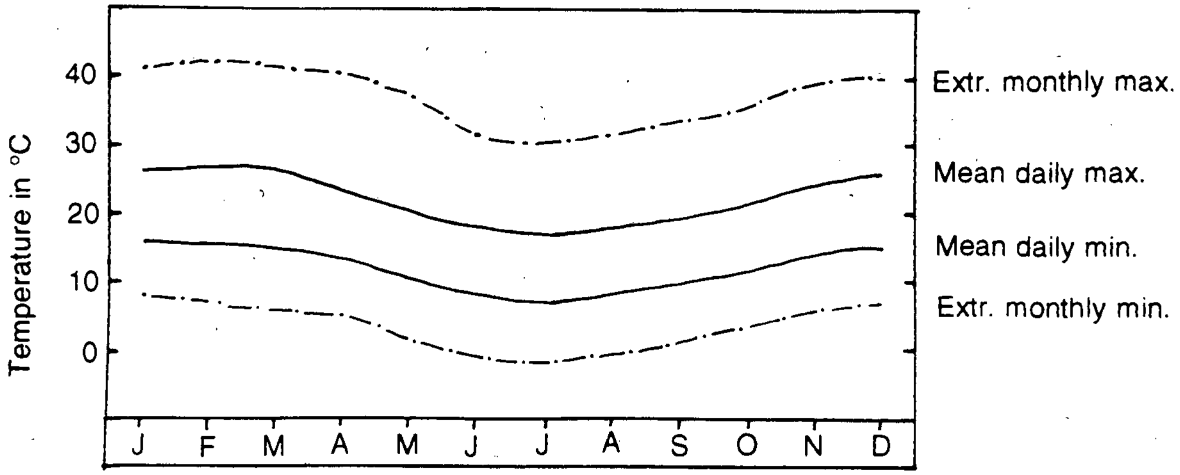


Figure 5 : Temperature, D.F. Malan Airport (After Schulze, 1965)

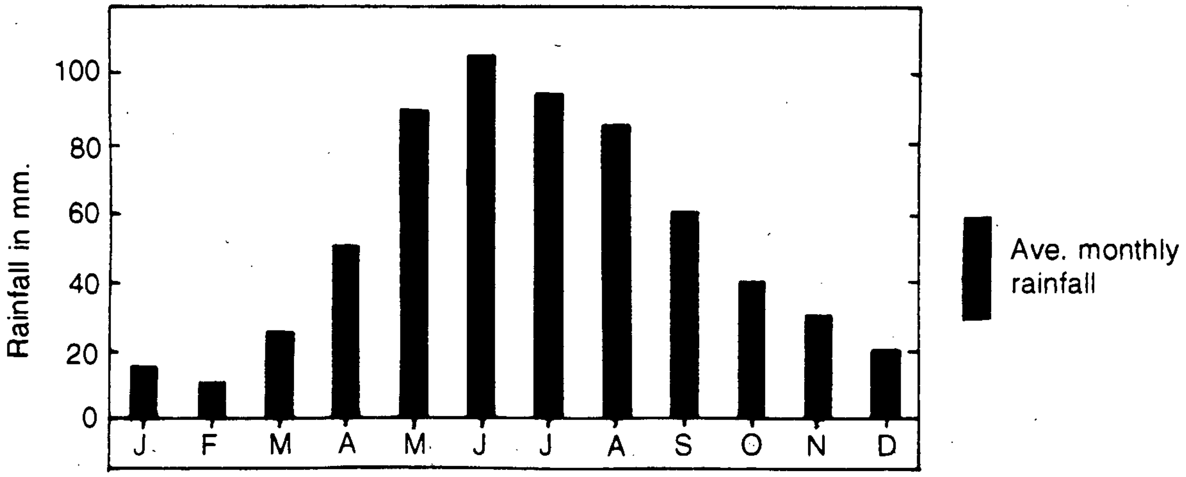


Figure 6 : Rainfall, D.F. Malan Airport (After Schulze, 1965)

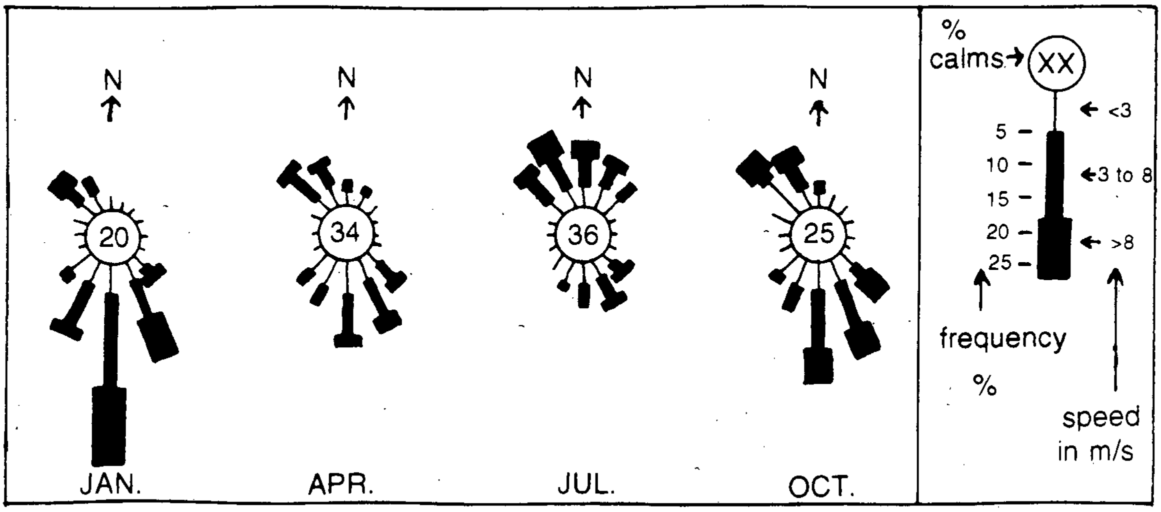


Figure 7 : Wind, D.F. Malan Airport (After Schulze, 1965)

Virtually the entire amount of precipitation is a result of the passage, from west to east, of cold frontal systems (mid-latitude cyclones) which travel over the south-western Cape after originating in the Atlantic Ocean. The rain from these systems usually takes the form of soft, soaking showers, although on occasions more intense precipitation results from the passage of very well-developed frontal systems. Thunderstorms occur very rarely, on no more than 5 occasions per year (King, 1983), and do not usually produce any significant rainfall. The frontal systems influence the area most frequently between May and September, but even during this wet period there are numerous spells of fine weather resulting from the presence of high pressure systems which separate the frontal systems.

A noteworthy feature of the rainfall pattern within the study area is the influence of topography on precipitation. Table Mountain, even though it lies outside the study area, is responsible for the high annual rainfall in the western parts of the Black River's catchment. Within this area, mean annual rainfall ranges from 1 200 mm at Kenilworth to 1 600 mm at Newlands. Annual rainfall over the flat Vygekraal catchment area is unlikely to vary much from the 625 mm recorded at D.F. Malan Airport. The Tygerberg Hills region receives a slightly higher annual rainfall (approximately 700 mm) than that of the Cape Flats.

The maximum rainfall received by an area within a short period, e.g., 24 hours or less, is more likely to determine run-off (and therefore soil erosion and sediment transport) than is the total rainfall received annually. Unfortunately, no accurate data seem to exist with regard to 24 hour rainfall maxima within the study area. However, bearing in mind the nature of Cape Town's rainfall, it is unlikely that figures of 50 mm are often exceeded within a 24 hour period, although in those areas where precipitation is affected by Table Mountain (from Rondebosch to Wynberg), it is probable that falls of 100 mm to 200 mm can occur within 24 hours.

2.4.3 Wind

The Cape Town area is noted for the windiness of its climate. During the summer months, in particular, persistent, strong, dry winds may blow, normally from a southerly or south-easterly direction, for days on end, often reaching (and sometimes exceeding) speeds of 60 km/hour (Figure 7). The Cape Flats region tends to be more exposed to these southerly or south-easterly winds, than is the Tygerberg Hills area. These summer winds are very active agents of soil erosion and sand transport, especially in the Vygekraal catchment.

During the winter, north-westerly winds associated with the passage of cold fronts blow sporadically over the area, and are usually accompanied by rain. These winds may also reach speeds of 60 km/hour or more, but they tend only to blow for one or two days at a time, and they usually alternate with periods of calm weather associated with high pressure systems. This is shown by the relatively high percentage of calms for July (Figure 7). The winter winds are not likely to be such powerful agents of soil erosion and transportation, since the surface material within the study area will be (on the whole) must moister, and thus more resistant to wind-induced mobilization, than would be the case during the dry summer period.

Hot, dry winds from the north-east blow occasionally, prior to the approach of a cold front, while cold, moist south-westerly winds sometimes blow, following the passage of a well defined frontal system. The frequencies and strengths of these north-easterlies and south-westerlies are, however, significantly lower than those of the summer south-easterlies and the winter north-westerlies.

2.5 LAND USE AND RESULTING VEGETATIVE COVER

Most of the land surface within the study area has been altered from its original natural state as a result of the continuing expansion of the suburbs of (and municipalities adjacent to) Cape Town. At many sites, this ongoing urbanization has resulted in an overall loss of vegetative cover, which in turn has rendered the affected land more vulnerable to soil erosion than was the case before urbanization. This situation is particularly true of the lower income housing areas on the Cape Flats, which lie within the catchment of the Vygekraal River. In the Tygerberg Hills region, vacant land and presently cultivated areas are being replaced by housing for the middle- and upper-income groups, since the areas already occupied by these groups (in the Black River catchment) are highly developed and possess little additional space for further expansion (C.M.P. Committee, 1988).

Soil loss within (or sediment yield from) the three sub-catchment areas may tentatively be assumed to be approximately equivalent to the amount of sediment received by the dredged area via the Black, Vygekraal and Elsieskraal Rivers.

2.5.1 Residential land

Land used for residential use occupies the larger part of the study area, particularly in the catchments of the Black and Vygekraal Rivers, and the southern part of the Elsieskraal catchment (Figure 8). The term "residential" is, however, a very broad one which includes many different types of land use and land management. This is especially true of a city such as Cape Town, which possesses such a great contrast in the housing conditions of its various income groups, with the highest density of population often found in those areas where the soils and vegetation have the lowest carrying capacity.

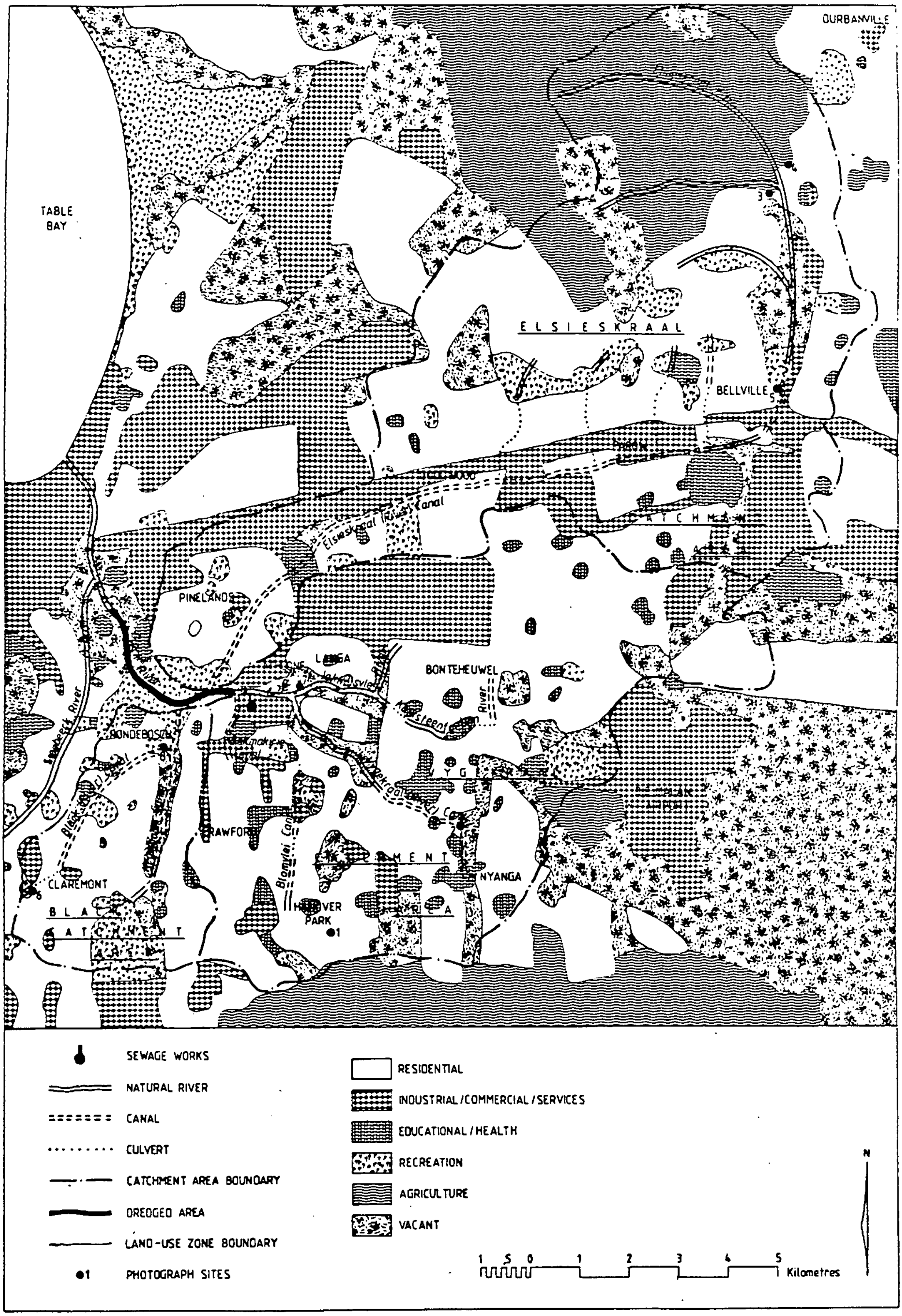


Figure 8 : Land use patterns in study area

Plate 1: Residential land (Hanover Park), showing unvegetated pavement

Plate 2: Residential and vacant land (Manenberg), adjacent to Vygekraal Canal

Such conditions are typical of the low income housing areas on the Cape Flats, which lie within the catchment of the Vygekraal River. These suburbs are characterized by low-cost housing surrounded by poorly vegetated gardens. Unvegetated, sand-covered sidewalks are a common feature of these areas (Plate 1). Such surfaces are extremely vulnerable to both water and wind-induced soil erosion and sediment transport. Measures have been taken in the past to alleviate the soil and sand loss, such as the application of laterite to stabilize the sand, attempts to grass the sidewalks, and the construction of concrete "stepping stones" for pedestrians. These measures have, however, owing to the frequent use of the sidewalks for both walking and the parking of cars, not been very successful in controlling sand loss. This mobilized sand is subsequently transported by both wind and water into the stormwater drainage system, and from there into the canals and rivers which eventually drain into the Vygekraal River. Small tracts of sparsely vegetated vacant land within the residential zones, usually fields used for the playing of ball games, are often situated next to canals (Plate 2), which results in further sand being washed or blown directly into the watercourses.

The catchment areas of the Black and Elsieskraal Rivers may be regarded as comprising the mostly middle- and upper-income housing of the so-called "southern suburbs" and "northern suburbs" respectively. In the already built-up areas, well grassed pavements and densely vegetated gardens ensure that far less soil or sand mobilization occurs (than on the Cape Flats). Thus, watercourses in these areas probably carry a significantly smaller amount of sediment, than do those within the Vygekraal catchment. One factor that can, however, result in high rates of soil or sand mobilization, is the disturbance of vegetated areas on vacant or cultivated land which is being cleared for the establishment of housing, as is the case in the areas of Durbanville and Kenridge (Plate 3). The relatively steep slopes in parts of these districts may further increase the likelihood of soil erosion due to run-off. Construction of new roads, and widening of existing ones, in these developing areas can introduce additional sandy material (such as builders' sand) to these parts (Plate 4). This sand is likely to be easily moved by either water or wind, and a large proportion of it is probably washed or blown into the Elsieskraal River or its tributaries.

2.5.2 Commercial, industrial and services land

These three land use categories have been grouped together as one for purposes of this study, since all of them have given rise to a similar type of surface cover, namely that comprising large buildings (or adjoining complexes of smaller ones), separated by open expanses usually which are usually tarred, concreted, or covered by gravel (laterite). Although run-off from such areas is often high, due to the impervious nature of the surface, their sediment yields are low, since there is normally little soil or sand present within them.

Most of the commercial land in the study area is situated within a 16 km-long belt, which is centred on Voortrekker Road which runs from Maitland to Bellville (Figure 8). Other, smaller tracts of land used for commercial purposes are scattered throughout the residential areas on the Cape Flats, and isolated commercial zones are situated in Claremont, Kenilworth, Pinelands, Kenridge and Durbanville. Land used for "service" use includes D.F. Malan Airport, Goodwood Cemetery, the Athlone Wastewater Treatment (Sewerage) Works and the Bellville Marshalling Yards, in addition to any areas occupied by roads or railways. Industrial land within the study area comprises the Epping Industria complex, large sections of Elsies River and Maitland, and isolated tracts on the Cape Flats.

Plate 3: Housing replacing agricultural and vacant land (Kenridge)

Plate 4: Road widening and construction (Kenridge), with builders' sand next to Elsieskraal River

2.5.3 Educational land

This category includes all land used to accommodate schools, colleges, universities and any other types of educational institutions. It is not possible to show each and every separate section of such land existing within the study area on a map such as Figure 8, although the larger educational complexes are indicated. These portions of land are scattered fairly evenly over the entire study area. Educational land will, in most cases, consist of a central building (or building complex) surrounded by grassed fields and other amenities used for recreational purposes by the students or scholars attending the institutions. Such sections of land are likely to be well managed, and thus should not be very vulnerable to soil erosion or subsequent sediment transport. In the lower income areas on the Cape Flats, however, a large number of school fields are either devoid of any grass, or are (at best) poorly vegetated.

2.5.4 Recreational land

Recreational land includes all public open space (Plate 5), public gardens (Plate 6), sports fields, golf courses, nature reserves/areas (such as those at Rondebosch, Durbanville, and Tygerberg), showgrounds or any other kind of public open space. These areas will generally consist of well-vegetated or grass-covered sections of land (with the possible exception of showgrounds), which should not suffer much soil erosion, and therefore not yield large quantities of sedimentary material. Some of these areas, such as those shown in Plates 5 and 6, have been carefully landscaped, and may be viewed as good examples of how to alleviate (or even prevent) soil erosion.

Plate 5: Recreational grassed land along Elsieskraal Canal (Bellville)

Plate 6: Claremont Gardens, with ponds on upper reaches of Black River

2.5.5 Agricultural land

This type of land use occurs only in the Tygerberg Hills region, mainly on their north-eastern slopes in the uppermost parts of the Elsieskraal River's catchment area (Figure 8). Farming activities comprise small-scale viticulture and various types of smallholdings. Soil erosion and sediment transport should not be of a great magnitude as long as appropriate measures are taken by the landowners to control run-off, particularly on steeply sloping land. Some soil is, however, likely to be removed from the farmlands and transported into, and by, the Elsieskraal River and its tributaries.

2.5.6 Vacant land

This is, like "residential", a broad term including many widely varying types of surface cover. "Vacant" essentially refers to land that is not presently being utilized for any of the uses previously discussed. Such areas may also include previously utilized land (such as the now disused quarries between Bellville and Kenridge), or land which is zoned for future use, but which has yet to be developed. Vacant land is either grassed, non-vegetated, or it may support the original natural indigenous vegetation (as is the case on the upper reaches of the Tygerberg Hills). Some of the vacant land on the Cape Flats is now covered by various species of alien acacias, while other parts of this region support a number of species of annual weeds.

Most of the non-vegetated vacant areas on the Cape Flats have their natural sand cover exposed to the forces of soil erosion and sediment transport. In some places, river banks are devoid of any vegetation, which results in the collapse of the banks due to erosion (Plate 7), and subsequent transport of this material into the Vygekraal

River. In the higher-income areas within the Black and Elsieskraal catchments, vacant land usually carries a substantial grass cover (Plate 8), and is thus not so susceptible to soil erosion.

2.6 CHARACTERISTICS OF THE CATCHMENT AREAS

2.6.1 Areas of catchments

The entire study area extends over 169,65 km². Of the three sub-catchments within the study area, that of the Elsieskraal River is the largest, covering an area of 86,84 km², including the adjoining municipalities of Pinelands, Goodwood, Parow, Bellville, and parts of Durbanville, as well as the adjacent Tygerberg Hills. The catchment of the Black River covers the smallest area, namely 15,90 km², and falls within the Rondebosch/Kenilworth/Lansdowne/Sybrand Park region. The Vygekraal River's catchment area is 66,91 km² in extent, and is situated mainly within the residential areas of the Cape Flats, and extends from Hanover Park in the south-west to Nyanga in the south-east and Bishop Lavis in the north-east, to Athlone in the north-west. According to Schumm (1977), there is an approximately linear negative correlation between the area of a catchment, and the sediment yield per unit area. This, however, is a very generalized statement, and it is far from certain how this factor would affect sediment production within the three sub-catchments comprising the study area.

Plate 7: Vacant land (Langa), showing natural sand cover exposed along eroded bank of Jakkalsvlei River

Plate 8: Confluence of Black River (canalized) and Kromboom Canal (Rondebosch), with adjacent grassed vacant and residential land

2.6.2 Sources, lengths and types of watercourses

The watercourses which comprise the drainage network within the study area have been classified according to the stream ordering scheme described by Strahler (1975). This system categorizes streams and rivers on the basis of their proximity to their source, and on their confluences with other watercourses, i.e., a first order stream is one in the uppermost part of the catchment, upstream of any confluence with any other watercourse; a second order stream (or river) is one which has been formed by the confluence of two first order streams; and a third order river is a watercourse resulting from the confluence of two second order rivers. Only the open channel watercourses within the study area are to be described, and the underground stormwater drains which flow into the canals (or rivers) will not be included in the catchment descriptions.

On the basis of this system, the Vygekraal River is the highest-order watercourse within the study area, i.e., the Black and Elsieskraal Rivers can be regarded as its major tributaries. The Vygekraal has its source in the Nyanga area, where it has been canalized. It flows north-westwards for 3 km through Manenberg and Surrey Estate in this form, as a first-order watercourse (Figure 2). Upon entering the Silvertown/Bridgetown area, the Vygekraal reverts to its natural state, and flows as such for a further 2,7 km until its confluence with the first order Blomvlei Canal (which flows north-wards from its source in Hanover Park). At this point, the Vygekraal becomes a second order river. Some 0,3 km downstream, the second order Jakkalsvlei River joins the Vygekraal, which thus becomes a third order river. The south-westward flowing Jakkalsvlei River is a product of the confluence of the first-order Jakkalsvlei and Kalksteenfontein streams (the latter being partially canalized), which have their sources in the Langa and Bonteheuwel areas respectively. From this point onwards, the Vygekraal flows westwards in its natural state. Its confluence with the first order Bokmakirie Canal (northward-flowing from its source in Athlone), occurs 1,1 km downstream of the confluence with the Jakkalsvlei River, and, at this point, the Vygekraal River enters the so-called dredged area. The Vygekraal/Elsieskraal confluence is situated 0,6 km downstream of this point, and the Vygekraal/Black confluence a further 0,7 km downstream. The Vygekraal River, as such, ends at this confluence, and the main water course, which from here onwards (downstream) flows in a north-westerly direction towards its mouth in Table Bay, is named the (lower) Black River. For the purposes of this study, the dredged area ends some 2,6 km downstream of the Vygekraal/Black confluence (Figure 2).

The upper (mostly canalized) portion of the Black River, i.e., that section of the watercourse within the sub-catchment area, has its source in the vicinity of Claremont Gardens, as a natural stream. Some 1 km from the source, however, this first order stream is canalized, and flows north-eastwards through Newlands and Rondebosch to join the first order Kromboom Canal (northward-flowing from its source in Kenilworth), approximately 4,5 km from Claremont gardens. From this confluence, the now second order Black River (Canal) flows northwards for 1 km until it joins the third order Vygekraal River.

The Elsieskraal River has its source in the Tygerberg Hills, some 10 km north-west of Bellville (Figure 2). It flows south-eastwards, and then south-wards, through the undulating terrain on the eastern slopes of the Tygerberg. It is joined in this area by two first order streams which flow through the Welgemoed area, some 6 km and 8 km from the source. Between 10 km and 11 km from its source, the Elsieskraal is canalized (in Bellville). This is followed immediately downstream by a 1 km stretch of natural river, the flow direction of which has turned westwards. At the downstream end of this section, the Elsieskraal is joined by a another first order stream, which flows south-wards off the Tygerberg. Below this confluence, the than do areas covered by more clay-rich soils, such as the Tygerberg. Previous studies (Simpson and Hemens, 1978; Simpson and Kemp, 1982) have shown that there is a fairly consistant linear relationship between the amount of of rainfall within a short period (such as 24 hours), and the quantity (volume) of run-off water that results from this precipitation. Mean annual run-off should also increase approximately proportionately to mean annual precipitation (Schumm, 1977).

Generally, it is probable that, during the wet winter period when most of the sediment transport (by water) occurs, the entire study area (with the probable exception of the dredged area) acts both as a zone of drainage and sediment production, and as a zone of transfer. The dredged area is likely, during this period, to act as a zone of deposition, owing to the sudden decrease in the sediment transporting capacity of the watercourses upon entering this area. During the dry summer, the zone of deposition will extend considerably further upstream in the watercourses, as a result of their decreased flow strengths and carrying capacities. The factor of wind, however, is likely to render this classification more complex, especially during the summer, since much (if not most) of the sediment transport during this period is performed by wind, rather than by water.

Human actions have greatly influenced the character of the drainage within the study area, both directly (by means of canalizing and culverting rivers), and indirectly (by the modification of the land surface as a result of urbanization). On the whole, urbanization leads to an increase in the area covered by impermeable surfaces (Beaumont, 1986; Wiseman, 1990), which results in an increase in both the amount and the speed of the run-off in affected areas. This can mean that a 1 in 50 year flood level may be transformed to a 1 in 20 year flood level. Services, such as the Athlone Sewerage Works and the Western Cape Regional Services Council works at Borcherds Quarry near D.F. Malan Airport also produce a run-off of effluent, which is pumped into rivers such as the Vygekraal, thereby increasing the downstream discharge of the river. Impermeable areas such as the Bellville Marshalling yards have, in particular, resulted in a local increase in run-off, which is reflected by a subsequent increase in the downstream discharge of the Elsieskraal River (Ninham Shand, 1979).

2.6.4 Obstructions

Obstructions to the flow of water in the watercouses within the study area are mostly in the form of road and railway bridges. These occur at fairly regular intervals along all of the rivers and canals in the area, with the largest structures being the road bridges which cross the lower Vygekraal/Black watercourse in the dredged area (Jan Smuts Avenue, Raapenberg Road, the N2, and the Black River Parkway). Numerous weirs also exist at various places along the watercourses. All of these structures may cause some degree of blockage at various times, especially if they collect (trap) vegetation and other debris carried by the rivers. Sediments are likely to accumulate to some degree on the upstream side of such obstructions, particularly during periods of decreasing flow, following floods or episodes of strong river flow resulting from heavy rainfall and rapid run-off in the catchment areas. According to some investigations (Ninham Shand, 1985a), the bridges downstream of the Vygekraal/Elsieskraal confluence are "not capable of passing the combined flow of these two rivers". Thus it is possible that, during strong flows, there might be a damming effect by these structures, which could result in very high river levels (and possible overbank flooding) upstream, in areas such as Pinelands, and on the low, flat ground of the Cape Flats. Accumulation of sediments on the river beds in these areas will further complicate these problems.

2.6.5 Abnormal flow patterns

Such events usually consist of short periods of extremely strong river flow (either in terms of velocity or discharge), which follow shortly after heavy rains in the catchment areas of the rivers. The time lag between these flow maxima and precipitation intensity maxima (the catchment concentration time) will be dependent on the nature of the land surface within the catchments, i.e., either a steep slope or an impervious surface will produce a rapid runoff, which will result in a very short concentration time.

Very few abnormal flow episodes in this area have been well-documented, but investigations were carried out on the cause and effects of the flooding of the Elsieskraal River during July 1985 (Ninham Shand, 1985b). The flooding resulted from very intense rainfall in the Tygerberg region (approximately 60 mm within 6 hours), with a concentration time of some 2 hours. This led to extremely high river levels and discharges, exceeding the estimated 1 in 20 year limits. Extensive overbank flooding occurred in Pinelands, Parow, Bellville, and Kenridge. At the height of the flood, discharge by the Elsieskraal River in Pinelands was in the order of 100 cumecs, some 10 times greater than measurements taken during this study following a rainy period. Such flooding can be further aggravated by backflooding from the so-called dredged area, prior sediment accumulation in the canals, and by blocked stormwater drains.

2.6.6 Soil erosion

Many, if not most, of the soil erosion problems in urbanized areas, are a result of a disturbance of geological normality (Brown, 1950). In the case of this study area, the effect has been further accelerated by the removal (or at least disturbance) of stabilizing vegetation. This has led to extensive erosion (by wind and water) of surface deposits, particularly the natural sand cover of the Cape Flats. Stream channel erosion of unconsolidated sand banks is also commonly occurring in this particular area. Even in better vegetated areas such as Pinelands, significant amounts of erosion occur next to the edge of the canalized Elsieskraal River (Ninham Shand, 1983b).

Gullying, and mass movements (such as soil creep) are likely to occur on steeper sloping land, such as that present in the Tygerberg Hills area. Scouring of river bed deposits by exceptionally strong flows will also produce sediment that is likely to be transported, and deposited in environments such as the dredged area. Short-term, man-induced disturbances such as soil erosion (and sediment transport) resulting from construction of roads, railways and buildings, will also act as a source of sediment. Previous research (Roberts and Pierce, 1974) has shown that sediment yields from urban catchments undergoing construction may be some 4 times greater than yields from agricultural land, and approximately 40 times greater than yields from well-grassed areas.

According to the SARRCUS (1981) soil erosion classification system, the sheet erosion (and wind erosion) occurring on the Cape Flats may be regarded as being severe in places, on the basis of the observed effects such as poor (or absent) vegetation cover, and mobile drifts of unconsolidated sand.

2.6.7 Deposition of sediments

Sediment deposition is controlled mainly by the flow velocity of the watercourses (especially bed flow, or shear velocity), and the grain size of the transported material. These processes, to be discussed in more detail in Chapters 3, 4, 5 and

6, will determine where sediment accumulation is most rapid, i.e., which parts of the study area are most likely to suffer from the so-called "silting up" of rivers (which, in the case of this study, is somewhat of a misnomer, since most of the sediments transported and deposited by the rivers in the study area consist of sand, rather than silt).

Overall, net sediment accumulation is greatest within the upper parts of the dredged area, while its lower section is not quite as affected. This is due to the fact that the sediments (mainly comprising the sand size fraction) are too coarse to be transported further downstream by the extremely slow-flowing lower Black River. Sediment deposition does occur, on a smaller scale, in the canals and tributaries higher in the catchment areas, but most of this material is moved further downstream during the winter period, by means of bed scouring, i.e., there is little or no net accumulation of sediments in these watercourses. Such sediments are usually present in various sections of the canalized Elsieskraal River between Bellville and Pinelands (Ninham Shand, 1983b), and also in the upper parts of the Vygekraal catchment.

CHAPTER 3 : STREAM FLOW AND SEDIMENT TRANSPORT

3.1 MEASUREMENT OF WATERCOURSE FLOWS (VELOCITIES AND DISCHARGES)

3.1.1 Aim

The aim of this section of the research was to determine the relative strengths of the flows in the Black, Vygekraal and Elsieskraal Rivers. Previous research has shown that sediment transport by rivers is, to some degree, dependent on both the quantities of discharge and on the shear velocity prevailing in the flow immediately above the river bed. Therefore, a calculation of both discharge and shear velocity for the three rivers in question should provide a measure of their relative sediment transporting powers. This in turn should indicate (perhaps only semi-quantitatively) the proportional contributions of each of the Black, Vygekraal and Elsieskraal Rivers to the total mass of sediments received by the dredged area each year. The grain size distribution of the stream sediments is not considered in this section of the study, since this aspect will be discussed in detail in Chapters 5 and 6.

3.1.2 **Method**

3.1.2.1 Measurement of discharges

There are two common methods of measuring stream discharge. The first involves the use of equations which relate the roughness of the bed and sides of the watercourse, to the discharge, whereas the second method consists of calculating discharge from a knowledge of mean stream velocity and cross-sectional area. The two most commonly used equations which relate roughness to discharge are the Manning Equation and the Chezy Equation (Blatt at al, 1972; Lewin, 1981). For the purposes of this study, however, it was decided not to use these equations, since it is unlikely that the correct roughness coefficient could be easily selected for a particular watercourse.

Instead, the method used was that by which the stream discharge could be calculated from the product of the mean stream velocity and stream cross-sectional area, since these could both be estimated to a reasonable degree of accuracy. The cross-sectional area was determined by measuring stream profiles at the selected measurement sites (Table 2), whereas mean velocity was derived from the measured maximum surface velocity of the stream. The maximum surface velocity was measured by timing cork floats over a distance of 10 m (the average of three readings was taken). Influence of wind on the movement of the corks was assumed to be insignificant, since virtually calm conditions prevailed at the time of the measurements. The measured maximum surface velocity was then multiplied by a factor of 0,7 (Shaw, 1988), in order to convert it to an assumed mean stream flow velocity. This conversion factor is usually used for flows shallower than 1 m, such as those at the measurement points. The mean velocities were then multiplied by the wetted cross-sectional stream area at the measurement point, in order to determine the stream discharges (measured in cumecs). These values are given in Table 3.

TABLE 2 : DESCRIPTIONS OF WATERCOURSES AT SELECTED SITES

Measurement	Type	Bank slope	Bed Gradient	Total bed width	Total vertical bank height	Wetted cross-section area	Season/ weather condition
		(degrees)	(percent)	(m)	(m)	(m^2)	
Black	canal	90	0,0040	12,0	1,6	0,090	summer
						1,094	winter (dry)
						9,254	winter (rain)
Elsieskraal	canal	30	0,0033	5,7	1,8	0,315	summer
						1,683	winter (dry)
						7,083	winter (rain)
Vygekraal	river	45	0,0040	5,0	2,0	1,987	summer
						1,987	winter (dry)
						6,710	winter (rain)

Note: River bank slope is approximate.

The measuring points for the Black and Elsieskraal Rivers were each sited between 100 m and 200 m upstream of the confluences of these watercourses with the main Vygekraal River channel in the dredged area. The Vygekraal measuring point was sited some 200 m upstream of the Athlone Waste Water Treatment (Sewerage) Works (hereafter referred to as the Athlone Works) outlet, so that this unnatural flow would not be incorporated into the discharge calculations. It is not likely that the positions chosen would be significantly affected by backflooding, and are probably close enough to the confluences with the dredged area so as to give representative readings of watercourse discharges into the dredged area. Strictly speaking, the

Bokmakirie Canal (which joins the Vygekraal immediately downstream of the Athlone Works outlet), should be included in the Vygekraal measurements, but it was excluded from the calculations since it is a very small watercourse (relative to the Vygekraal River) and as such is unlikely to make a significant contribution to the total flow entering the dredged area from the Vygekraal catchment.

TABLE 3 : FLOW (DISCHARGE) DETAILS OF WATERCOURSES

Measure -ment site	Season/ weather	Wet. bed width	Max. depth	Ave. depth	Wet. perimeter	Cross-section area	Max. surface vel.	Ass. mean vel.	Discharge	Percent. contri-bution
		(m)	(m)	(m)	(m)	(m^2)	(m/s)	(m/s)	(m^3/s)	
Black	summer	2,60	0,15	0,03	3,00	0,090	0,555	0,388	0,035	5,2
	winter (dry)	12,00	0,27	0,14	12,50	1,094	0,625	0,437	0,478	21,7
	winter (rain)	12,00	0,95	0,83	13,86	9,254	1,316	0,921	8,525	28,3
Elsies-kraal	summer	4,50	0,14	0,07	4,55	0,315	0,442	0,309	0,097	14,6
	winter (dry)	5,70	0,40	0,29	6,20	1,683	0,625	0,437	0,736	33,3
	winter (rain)	5,70	1,15	1,05	9,00	7,083	2,194	1,536	10,878	36,2
Vyge-kraal	summer	5,00	0,48	0,37	6,00	1,987	0,385	0,269	0,535	80,2
	winter (dry)	5,00	0,48	0,37	6,00	1,987	0,714	0,499	0,993	45,0
	winter (rain)	5,00	1,20	1,10	8,20	6,710	2,274	1,592	10,681	35,5

Note: For the percentage contributions, the totals for the summer, winter (dry) and winter (rain) measurements each total 100%.

Three sets of discharge values were calculated from measurements of stream velocity. These observations were taken during three contrasting weather conditions: a first set during March 1990 at the end of the dry season when river flows were at their weakest; a second set in July, immediately following a rainy period in winter; and a third set in August during a drier winter spell.

3.1.2.2 *Calculation of shear velocities and sediment transport rates*

Shear velocities in the watercourses were not physically measured in the field, since suitable equipment was not available. Such parameters, however, can be calculated quite accurately using theoretical formulae. One such formula is given by Blatt et al (1972), and it has the form:

$$(\text{shear velocity})^2 = \frac{g \cdot A \cdot S}{P}$$

where g = acceleration due to gravity
A = cross-sectional area of stream
S = slope of stream bed
P = wetted perimeter

Acceleration due to gravity (g) is a known constant at 9,8 m/s^2. The cross-sectional areas and wetted perimeters of the stream were physically measured in the field, while the slopes of the stream beds were calculated from contours on 1:10 000 orthophoto maps of the study area. This formula was thus used in order to calculate the shear velocities at the selected measuring points (the points used were the same as those in section 3.1.2.1). As in section 3.1.2.1, three different sets of shear velocities were calculated, one each for summer, winter (dry), and winter (wet). Assumptions made in these calculations were:

i. Average depth remains constant in vicinity of measuring point.

ii. Flow is steady over a certain time span.

iii. Slope is constant around measuring point.

Transport of sand-dominated sediments (such as those within the study area) usually takes place by means of bedload movement, which occurs in the form of saltation (this aspect will be discussed in more detail in Chapter 6). Transport rates of such saltating sediment are predictable in terms of water velocities very close to the stream bed, within the saltation zone (Bagnold, 1973). This so-called shear velocity (as calculated above) can then be used in order to estimate a sediment transport rate.

According to Leeder (1982), a potential sediment transport rate (per unit bed width) may be regarded as being proportional to the cube of the shear velocity. This relationship may be written as:

potential sediment transport rate = 0,112 . $(\text{shear velocity})^3$

In order to calculate the total potential sediment transport rate across the entire stream bed at a given measuring point, the potential sediment transport rate must be multiplied by the bed width at that point. The values obtained are presented in Table 4. Such a potential sediment transport rate may be regarded as being the equivalent of the stream capacity, i.e., the maximum load a stream can carry. Previous research undertaken (Reid and Frostick, 1987), however, has shown that in rivers containing man-made obstacles (such as those of the study area), relationships between stream power (represented either by discharge or shear velocity) and sediment transport rates are more complex and therefore may not be simply represented by a single formula. Thus, the values given in Table 4 should not be regarded as completely accurate, although they probably do convey a reasonably representative proportional distribution of sediment transport within the study area.

3.2 RESULTS

3.2.1 Discharges

The discharges calculated at the three measuring points are shown in Table 3. For the summer situation, the flows (in cumecs) for the watercourses are:

Black:	0,03
Vygekraal:	0,53
Elsieskraal:	0,10

Expressed in terms of proportional (percentage) contributions to the total flow received by the dredged area from these three watercourses, these values are:

Black:	5 %
Vygekraal:	80 %
Elsieskraal:	15 %

The corresponding values, calculated for the dry winter conditions, are (flows in cumecs):

Black:	0,48
Vygekraal:	0,99
Elsieskraal:	0,74

In terms of percentage contributions, these are:

Black:	22 %
Vygekraal:	45 %
Elsieskraal:	33 %

The wet winter conditions flows (in cumecs are):

Black:	8,52
Vygekraal:	10,68
Elsieskraal:	10,88

In terms of percentage contributions, these are:

Black:	28 %
Vygekraal:	36 %
Elsieskraal:	36 %

It is therefore apparent that, while the Vygekraal watercourse contributes the highest proportion to the total flow under the two drier weather conditions, the actual proportional contribution itself decreases as the overall flow strengths increase. The Elsieskraal has a marginally higher discharge than the Vygekraal under the wet winter conditions. The proportional contributions of the Elsieskraal and Black watercourses (to the total flow) increase as overall flow strengths increase. This effect might be explained by the higher rainfalls (with respect to the Vygekraal catchment) that are received by the Black catchment, and the upper parts of the Elsieskraal catchment. Under all conditions, however, the Black has the least discharge of the three watercourses.

Some previous monitoring of river flows within the study area has been undertaken (Morrison, 1982; Pitt, 1987; Pitt, 1989). A summary of the data presented in these reports can be used to compare the percentage/proportional flow contributions of the Black, Vygekraal and Elsieskraal watercourses in previous years, to the values presented in this study. These earlier calculations were made by the use of mass balance equations, using conductivity and chloride values measured over certain periods. It is not stated, however, what the length of these periods was, or whether the figures derived followed one singular measurement, or were the result of continuous monitoring throughout the year.

The averaged values for the period 1976/1980 are:

Black:	4 %
Vygekraal:	82 %
Elsieskraal	14 %

For the 1982/1985 period, corresponding values are:

Black:	3 %
Vygekraal	88 %
Elsieskraal:	9 %

The figures for the 1985/1988 period are:

Black:	3 %
Vygekraal:	91 %
Elsieskraal:	6 %

Comparisons between these earlier data, and values derived by this study, may, however, not be valid, owing to the differences in the methodologies used to determine the discharges. Nevertheless, it would seem, from the earlier studies, that the proportional contribution of the Vygekraal was increasing (between 1976 and 1988), whereas those of the Black and Elsieskraal were decreasing with time. The 1985/1988 proportional contribution values for the Vygekraal appear to be significantly higher than the corresponding values obtained in this study (particularly the winter readings). It remains uncertain as to which of the three sets of measurements presented in this study are the most representative in terms of an overall average annual discharge pattern.

3.2.2 Potential sediment transport rates from shear velocities

With respect to the study area, no previous research data are available within this field. The results from the theoretical calculations performed in this study are given in Table 4. The potential sediment transport rates, calculated from the shear velocities (as explained in section 3.1.2.2), are given in grams per second. These values have been determined for summer, dry winter and wet winter conditions. The values for the summer flows, with the percentage contribution to the total potential sediment transport given in brackets, are:

Black:	11	(1 %)
Vygekraal:	829	(93 %)
Elsieskraal:	52	(6 %)
Total:	892	

Corresponding values for the dry winter period are:

Black:	262	(16 %)
Vygekraal:	829	(51 %)
Elsieskraal:	530	(33 %)
Total:	1 621	

The values calculated for the wet winter period are:

Black:	5 714	(50 %)
Vygekraal:	3 211	(28 %)
Elsieskraal:	2 566	(22 %)
Total:	11 491	

TABLE 4 : POTENTIAL SEDIMENT TRANSPORT RATES OF WATERCOURSES

Measurement site	Season/ weather	Shear velocity	Unit sediment transport rate	Bed width	Total watercourse sediment transport rate	Estimated annual sediment transport rate	Percentage potential contribution
		(cm/s)	(g/m/s)	(m)	(g/s)	(tons/ year)	
Black	summer	3,4	4,4	2,6	11,4	359	1,3
	winter (dry)	5,8	21,8	12,0	261,6	8 250	16,1
	winter (rain)	16,2	476,2	12,0	5 714,4	180 209	49,7
Elsies-kraal	summer	4,7	11,6	4,5	52,2	1 646	5,8
	winter (dry)	9,4	93,0	5,7	530,1	16 714	32,7
	winter (rain)	15,9	450,2	5,7	2 566,2	80 928	22,3
Vygekraal	summer	11,4	165,9	5,0	829,5	26 159	92,9
	winter (dry)	11,4	165,9	5,0	829,5	26 159	51,2
	winter (rain)	17,9	642,3	5,0	3 211,5	101 278	28,0

Note: For the percentage contributions, the totals for the summer, winter (dry) and winter (rain) measurements each total 100%.

If these potential sediment transport rates are converted to tons per year, the values for the summer flows become:

Black:	359
Vygekraal:	26 159
Elsieskraal:	1 646
Total:	28 164

The corresponding values for the dry winter flows are:

Black:	8 250
Vygekraal:	26 159
Elsieskraal:	16 714
Total:	51 123

It is unlikely that the figures for the wet winter flows are representative of flow strengths over long periods, so it would not appear to be meaningful to convert them to annual sediment transport rates. Although the potential transport rate of the Vygekraal is the greatest of the three watercourses during both seasons, it shows no increase from summer to winter (on the basis of this study), whereas the transport rates of the Black (especially) and the Elsieskraal show a marked increase in their winter rates. An overall annual transport rate should be intermediate between the summer and winter values. Regarding such a rate, the Vygekraal is probably the major transporter (potentially, at least) of alluvial material within the study area.

3.3 INTERPRETATION

3.3.1 Influence of watercourse discharge on sediment load

Previous research (Bagnold 1968; Bhowmik and Demissie, 1986) has shown that there is a definite relationship between stream discharge and the amount of sediment moved by that stream. These studies have shown this correlation to be approximately lognormal (Figure 9). According to such studies, flood events are responsible for transporting some 80 % of the annual sediment load. Surface geology, sand or soil cover within the catchments of different streams will also have a bearing on the sediment load carried by those rivers, but this aspect will be discussed in more detail in Chapter 6.

If the mean values of the three sets of discharge measurements taken for the Black, Vygekraal and Elsieskraal Rivers are plotted on a sediment load versus stream discharge graph (Figure 9), the approximate implied sediment loads transported (in tons per year) are:

Black:	9 500	(24 %)
Vygekraal:	16 000	(41 %)
Elsieskraal:	13 500	(35 %)
Total:	39 000	

The sediment removed from the dredged area (during autumn 1990) by the Cape Town City Council had a volume of 10 800 m³. If it is assumed that the mean specific gravity of this material was 2,65 g/cm³ (that of quartz, since most of the sediments are thought to comprise silica sand), then the mass of this dredged material was 28 620 tons. Bearing in mind that this sediment was only dredged from the upper two-thirds of the dredged area, it can be assumed that a slightly greater quantity of sediment is deposited annually in the entire dredged area. Such an amount is likely to compare favourably with the 39 000 tons read from Figure 9. Another assumption that has to be made in these kind of calculations, is that the sediments transported by the rivers within the study area take less than one year to reach the dredged area. Once again, the Vygekraal is shown to be able to transport the most sediment, the Elsieskraal an intermediate amount, and the Black the least amount of sediment. These calculations do not, however, consider (and are not dependent on) the amount of sediment made available to the rivers in their catchment areas. They only determine the potential transporting power of the watercourses in question.

3.3.2 Relationship between shear velocity and sediment transport

The sediment transport rates determined from shear velocities are a measure of the watercourses' total (maximum) potential power to transport sediment, assuming that such material is delivered to them by their tributaries (and also by the stormwater drainage networks within their catchments). Therefore, if sediment transport by rivers (usually in the form of bedload movement for sand-dominated material such as that in the study area) is less than this maximum potential, this is due to a lack of sediment supply (Mantz and Emmett, 1986), and the power, determined by shear velocity, used in moving such bedloads usually represents less than 1 % of the total stream power, which is more a function of discharge.

This is probably the case within the catchment area of the Black River. Therefore shear velocity-derived potential sediment transport rates (such as those given in section 3.2.2) for this watercourse are more than likely to overestimate the amount of sediment delivered into the dredged area. The values obtained for the wet winter situation, in particular, may be regarded as excessive. The same conditions probably apply, to a lesser degree, to the measurements made for the Elsieskraal River. In comparing the total estimates for sediments delivered to the dredged area, it should be expected that an overall annual quantity is likely to be intermediate between such amounts derived from either summer or winter measurements. Thus the comparison between the estimated amount of material removed annually from the dredged area (somewhere moderately in excess of 28 000 tons), is favourable with respect to the annual potential transport rates based on summer flow (28 164 tons), and winter flow (51 123 tons).

Assuming that all (or most) of the sediments delivered by the catchment areas to the rivers are transported into the dredged area, no significant differences (in quantity) should exist between material removed from the dredged area, and material produced within the catchments. Schumm (1977) has estimated that average sediment yield from urbanized areas with similar rainfall and temperature conditions to those of Cape Town is approximately 120 tons per km² per year. Since the total study area is some 170 km² in extent, it should deliver 20 400 tons of sediment per year into its watercourses, and ultimately into the dredged area. The fact that this value is considerably lower than the actual amount of sediment removed from the dredged area can probably be explained by the presence of vast quantities of easily transported unconsolidated sand on the Cape Flats, and also, perhaps, by the possibility that a significant amount of this sand may be blown by wind directly into the dredged area.

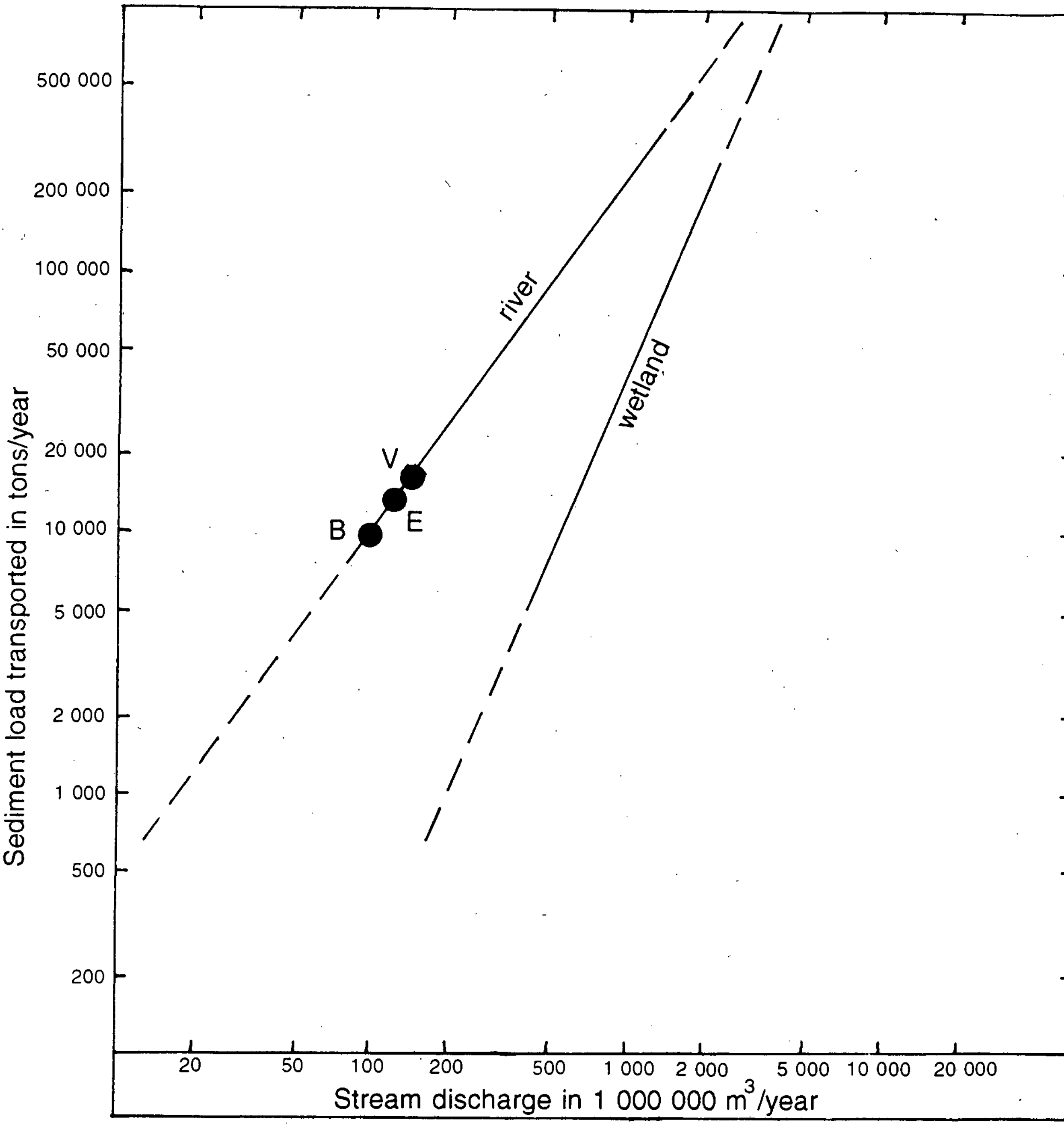


Figure 9 : ***Relationship between annual sediment load, and stream discharge (After Bhowmik and Demissie, 1986)***

CHAPTER 4 : SEDIMENT SAMPLING AND SAMPLE PREPARATION

4.1 SAMPLING OF WATERCOURSE SEDIMENTS

4.1.1 Aim

The primary aim of this sampling programme was to generate seven representative, evenly spread sets of watercourse sediment samples, one each from the three sub-catchments within the study area (those of the Black, Vygekraal and Elsieskraal Rivers), and the other four representing the upper, middle, lower, and extreme lower sections of the dredged area. These seven sample groups were to be used in subsequent particle size analyses, X-ray diffraction investigations, microscopic studies, and statistical analyses of the sediments.

4.1.2 Method

Owing to time constraints, sediment samples were only collected from the watercourses during January and February 1990, i.e., during the latter part of the dry summer season, before the commencement of the 1990 dredging operations. Samples were obtained by means of scooping from the uppermost 10 cm of sediment accumulations on the beds of the watercourses (no coring or auguring was employed). Sediment samples were taken from the major watercourses (Black, Vygekraal, Elsieskraal), and also from their tributaries. Sampling was carried out as far upstream as was possible in all cases. The spacing of the sampling points was kept as consistent as was possible, although this was in places determined by the availability of sedimentary material at proposed sampling sites.

Sampling sites in the watercourses within the catchment areas are shown on Figure 10, and those within the dredged area are indicated on Figure 11. The original sample set consisted of 15 samples from the Black catchment, 29 samples from the Vygekraal catchment, 29 samples from the Elsieskraal catchment, and 33 from the dredged area. Samples within the catchment areas were spaced between 0,5 km and 1 km apart. Since the watercourse in the dredged area is between 20 m and 40 m in width, 2 or 3 samples were taken at each site, distributed across the channel, some 10 m to 20 m apart. Owing to time constraints and analytical limitations, only some of the samples from the catchment areas were analysed (Figures 10 and 11). These comprised 8 samples from the Black catchment, 17 samples from the Vygekraal catchment, and 14 samples from the Elsieskraal catchment. All 33 of the dredged area samples were analysed.

The dredged area has been subdivided into four sections, for the purposes of sample grouping. These sections are: the upper dredged area (from the Jan Smuts Avenue bridge downstream to the Elsieskraal/Vygekraal confluence); the middle dredged area (from the Elsieskraal/Vygekraal confluence downstream to the Black/Vygekraal confluence); the lower dredged area (from the Black/Vygekraal confluence downstream to the entrance to the municipal pump station at Raapenberg); and the extreme lower dredged area (from the Raapenberg pump station entrance downstream to the Black River Parkway bridge).

4.2.3.2 *Amount of sand in samples*

Sand is the major constituent of most of the stream sediments sampled within the study area. This fact is clearly shown by the overall mean sand content of all samples, namely 88 %. Group mean sand contents are; Black catchment 80 %; Vygekraal catchment 97 %; Elsieskraal catchment 83 %; upper dredged area 99 %; middle dredged area 99 %; lower dredged area 99 %; and extreme lower dredged area 67 %.

Within the Black catchment, sand content varies from less than 80 % in the upper part, to over 90 % in the middle sector, decreasing to less than 60 % in the lower part. Sand contents within the Vygekraal catchment are generally in excess of 90 %, while those of the Elsieskraal catchment range from around 70 % in the upper part, to over 90 % in the lower part (Figure 13).

Sand contents in the upper, middle and lower parts of the dredged area all exceed 90 %, with a number of samples from this area comprising 100 % sand. Only in the extreme lower sector of the dredged area does this pattern change, in that the sand content decreases to as little as 30 %. In most other parts of the extreme lower dredged area, however, sand content varies from 40 % to 90 %.

4.2.3.3 *Amount of organic matter in samples*

Organic matter is very much a minor constituent of most of the sediment samples. No significant amounts, i.e., less than 1 %, of organics were detected in any samples from the Black catchment, Vygekraal catchment, lower Elsieskraal catchment, upper, middle, or lower parts of the dredged area (Figure 14). Only in the upper Elsieskraal catchment (organic content up to 8 %), and the extreme lower dredged area (organic content up to 29 % at sample site BLA16a), were significant amounts of organic matter present in the samples.

4.2.4 Interpretation

The gravel content of the sediment samples (those particles coarser than -1 ϕ, or 2 mm) is almost entirely composed of material of anthropogenic origins. Most commonly occurring substances include: fragments of glass, shell and bone; pieces of mortar (concrete/cement): fragments of road aggregate; and aggregates of ferricrete (or laterite), usually derived from parking lots and untarred roads. The glass, shell and bone fragments are probably introduced into the watercourses via the stormwater drainage network, and the mortar is likely to have been derived from construction sites, pavements, and walls. The road aggregate material used is most commonly hornfels and slate from the meta-sediments of the Malmesbury Group (Mountain et al, 1990). These gravel components of the samples are unlikely to be the result of natural watercourse transport and sorting processes, as the relatively weak flows of the rivers and canals within the study area would not be capable of transporting such coarse material, except perhaps during abnormally strong flow conditions. It is thus likely that the majority of this coarse material has entered the watercourses at (or very close to) the sites of the samples from which they were extracted. This situation should be particularly true of the very slight flows in the lower parts of the dredged area. It is possible, however, during rare episodes of extremely high flow, that such coarse material may be transported by the watercourses to the dredged area.

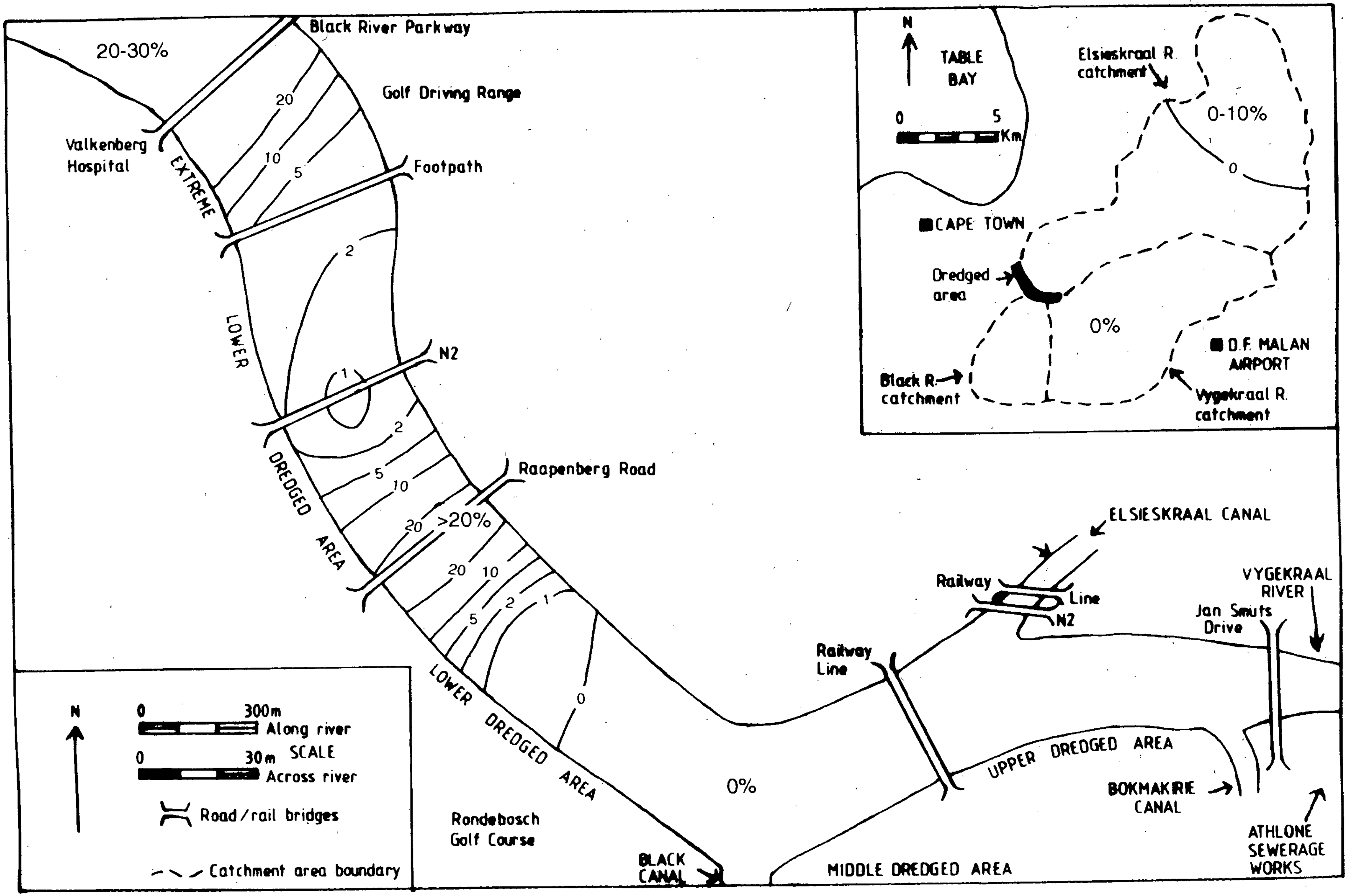


Figure 14 : Organics % (by mass) of sediments within the dredged area (main map) and catchment areas (inset)

CHAPTER 5 : FINE FRACTION ANALYSIS

5.1 AIMS

The aims of this section of the study are:

i. The determination of the silt and clay contents of the sediment samples.

ii. A comparison of the particle (grain) size distributions of the fine fractions of dredged area samples with those of Elsieskraal catchment samples fine fractions. A similarity in the size distributions of both sets of fine fractions could indicate that some (if not most) of the sediments within this size range (that are deposited in the dredged area) could originate from within the Elsieskraal catchment.

5.2 METHOD

The fine fractions of the sediment samples were analysed for particle size distribution on a sedigraph particle size analyser, the technical details of which are described in Appendix 2. The concentration of a suspended sediment sample (as prepared in Chapter 4) is measured by means of passing X-rays through the suspended material. The sediment concentration is then plotted against elapsed time. Since grains will be continuously settling out of the suspension (according to the principles of Stokes' settling law, i.e., the larger a grain, the more rapid is its settling rate), the concentration of suspended sediment can be expected to decrease with time. The settling velocities are then derived from the rate of decrease of suspension concentration. Grain (particle) size distribution is then determined (by means of a computer programme based on Stokes' settling law) from the settling velocities. Graphical statistical size distribution parameters were then calculated (also by computer) from the size distribution, using the formulae devised by Folk and Ward (1957).

Of those samples containing fine sediments, samples BLA12c, BLA14b, BLA14c, ELS8, ELS9 and ELS11 were not analysed on the sedigraph, since the quantity of fine material obtained in the preparation was not sufficient to be analysed on the sedigraph. Instead, the mean silt:clay ratios for the analysed samples (from each area) were applied in the calculation of their silt and clay contents.

5.3 RESULTS

All results from the preliminary particle size analyses are presented in Appendix 3, i.e., the determination of the mass percentage proportions of the gravel, sand, silt, clay and organic fractions of the watercourse sediment samples. Particle size analysis of the fine (silt and clay) fraction is not able to generate a size distribution for the entire fine fraction, since it is virtually impossible to get some of the grains within the clay size range (those smaller than 8 ϕ) to settle out of suspension within a short time. Therefore the particle size analysis represents that material in the size range from 8 ϕ to 4 ϕ. The silt/clay cut-off has been taken as 8 ϕ, according to the widely used Udden-Wentworth scale.

5.3.1 Amount of silt in samples

Grains within the silt size range (8 ϕ to 4 ϕ) are present only in samples from the upper Elsieskraal catchment and the extreme lower dredged area (Figure 15). Within the extreme lower dredged area, silt contents vary from 0 % to 19 % at sample site BLA13b. The greatest silt content value within the upper Elsieskraal catchment is at sample sites ELS3 and ELS5, namely 15 %. Mean silt content values for both areas are 8 %.

5.3.2 Amount of clay in samples

As in the case of the silt contents of samples, clay is present only in samples from the upper Elsieskraal catchment and the extreme lower dredged area. In the former area, the highest clay content is 17 % at sample site ELS3, while in the latter area, the most clay-rich sample was found to be BLA13b, with 12 % clay. Mean clay content values are 6 % and 5 % for the upper Elsieskraal catchment and the extreme lower dredged area respectively (Figure 16).

5.3.3 Mean, median and modal sizes of fine fractions

These values, obtained from the particle size analyses on the sedigraph, are presented in tabulated form in Appendix 4, and the actual size distribution plots (of some selected representative samples) are shown in Appendix 5. There is some variation between mean, median and modal grain sizes of the samples, in that the mean size values are smaller (i.e., the ϕ values are larger) than are the median size values, which in turn are smaller than the modal size values. This is true for all 12 samples analysed on the sedigraph.

Mean sizes of dredged area samples vary from 9,2 ϕ to 7,3 ϕ, while those of the Elsieskraal samples are between 8,6 ϕ and 7,6 ϕ. Median values for the dredged area lie between 8,8 ϕ and 6,2 ϕ, whereas those of the Elsieskraal samples range from 8,3 ϕ to 6,8 ϕ. The modal sizes for the samples from the dredged area vary from 8,4 ϕ to 5,0 ϕ. There are no distinct trends for any of these parameters within the dredged area, although the values for the samples at BLA12a and BLA12b are notably smaller (with respect to grain size) than are the values for the other samples within the dredged area.

5.3.4 Sorting of fine fractions

Sorting values (also given in ϕ units) for the dredged area samples vary from 2,5 ϕ to 2,9 ϕ, while those for the Elsieskraal samples are between 2,7 ϕ and 3,0 ϕ. Therefore all of these samples may be regarded as being very poorly sorted (Leeder, 1982). No distinct trends were observed within the dredged area.

5.3.5 Skewness of fine fractions

All of the samples analysed on the sedigraph display positive skewness (finely skewed). The dredged area samples have skewness values ranging from +0,1 to +0,5, while the Elsieskraal values lie between +0,1 and +0,4. Samples ELS3, BLA12a and BLA12b are the only samples to have skewness values of less than +0,2.

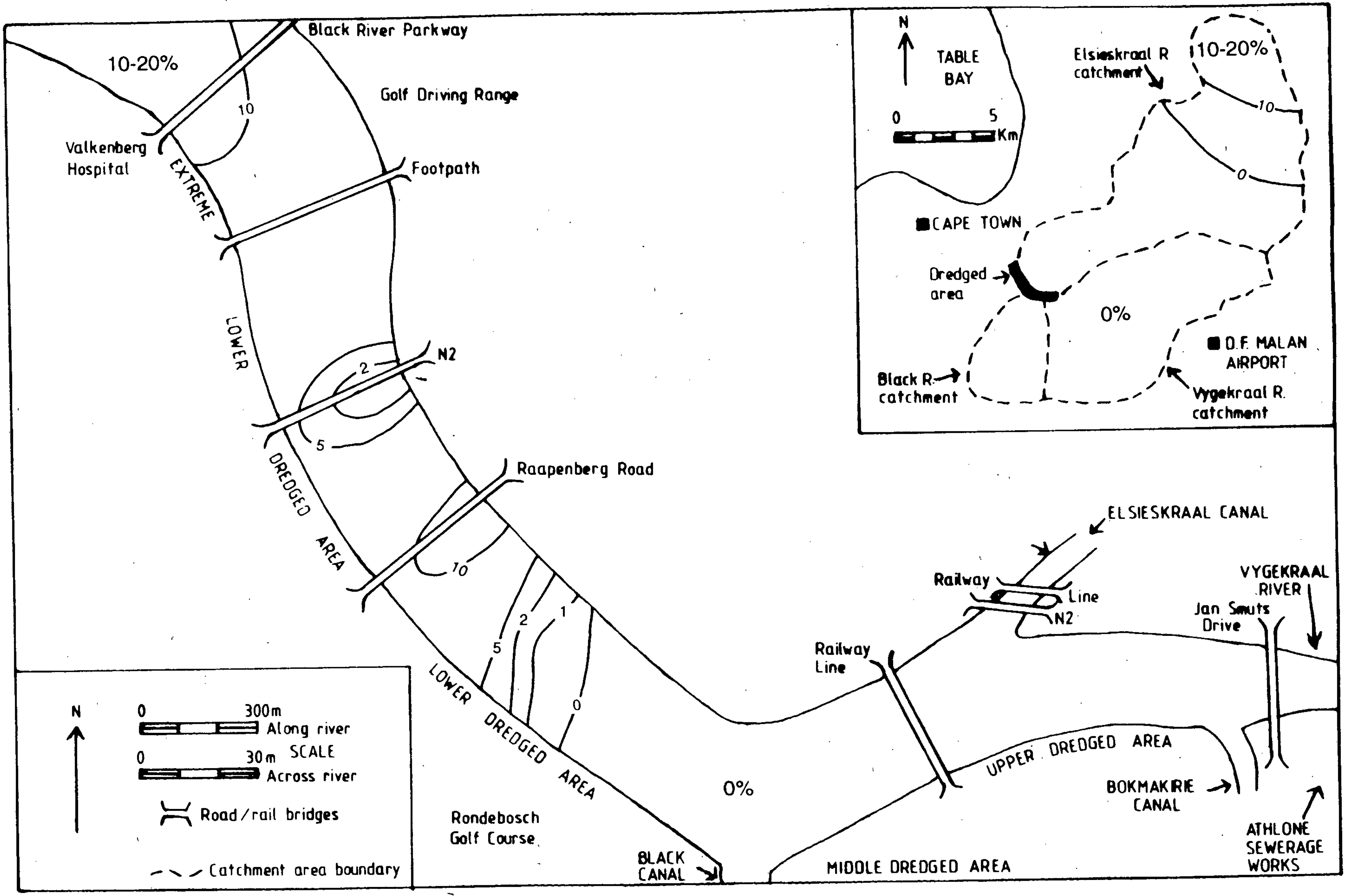


Figure 15 : Silt % (by mass) of sediments within the dredged area (main map) and catchment areas (inset)

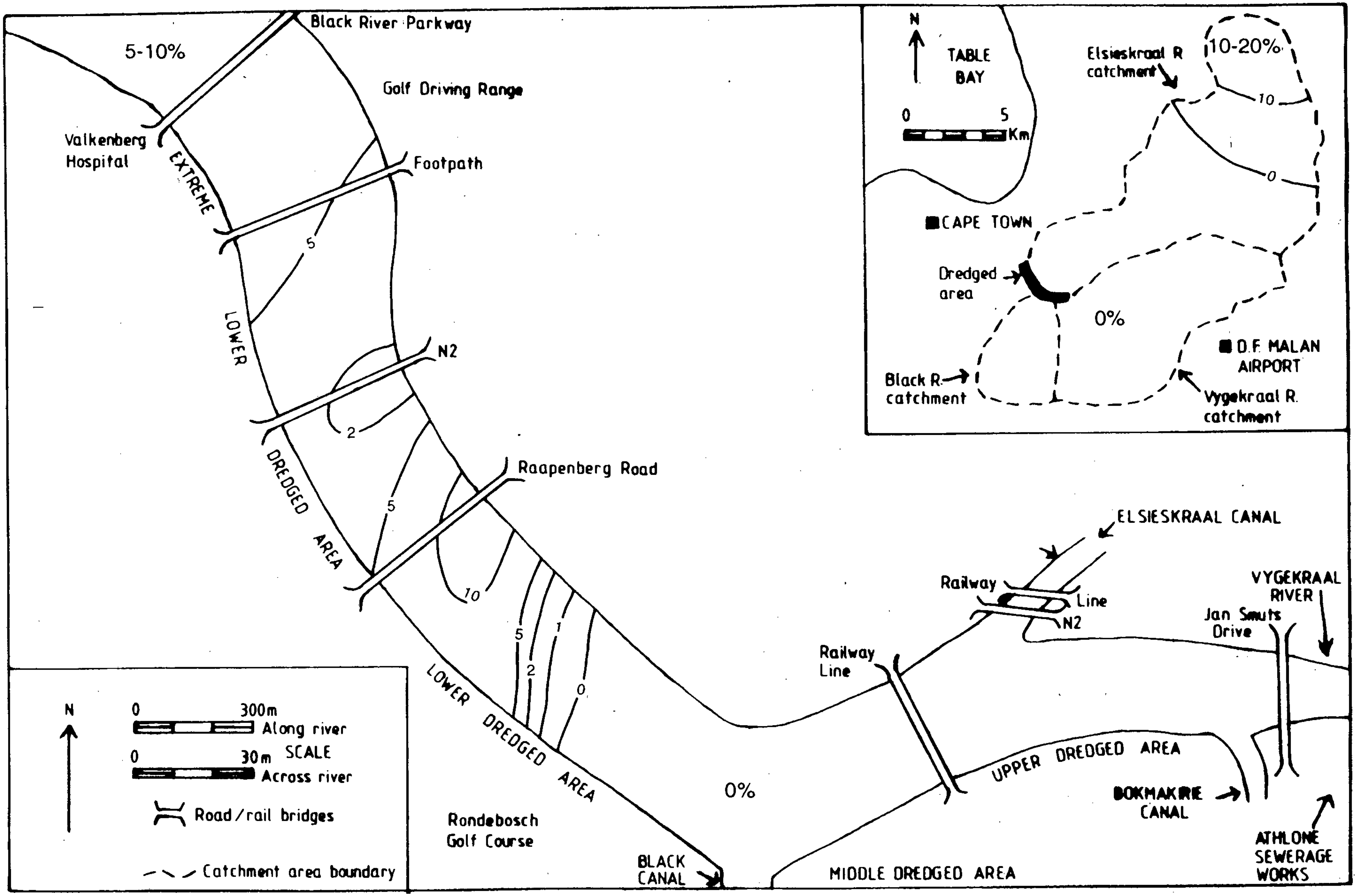


Figure 16 : Clay % (by mass) of sediments within the dredged area (main map) and catchment areas (inset)

5.3.6 Kurtosis of fine fractions

The kurtosis values of the samples (i.e., the "peakedness" of the grain size distribution on a frequency curve) lie between 0,7 and 1,0 (mesokurtic and platykurtic), although most of the dredged area samples have values of between 0,8 and 0,9 (platykurtic). Only sample ELS6 has a distinctly mesokurtic value, namely 1,0.

5.4 INTERPRETATION

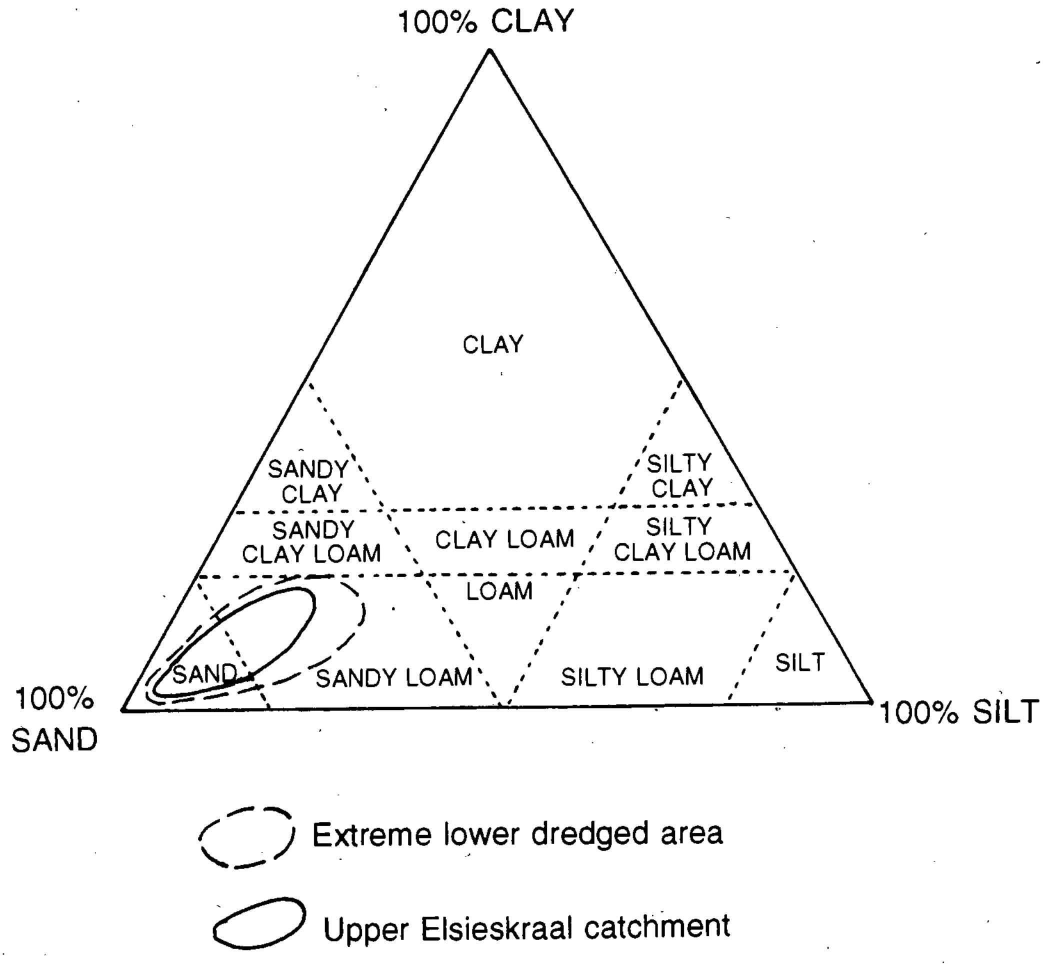
Although some of the characteristics of the grain size distributions of sediments deposited in a downstream environment (such as the extreme lower dredged area) will have been acquired (or superimposed) during transport from the source area, other properties of the source material will be inherited by the downstream deposit. These vestiges of the initial properties may, however, be modified during transport and deposition.

The fine fractions of the sediments in the extreme lower dredged area possess markedly similar grain size distribution properties to those of sediments in the upper Elsieskraal catchment, particularly with respect to their modal grain sizes (Appendices 4 and 5). This is especially so in the case of a comparison between the size distributions for samples ELS5 and ELS6 (representing the source area), and BLA15b and BLA16a (representing the deposits in the extreme lower dredged area). A plot, comparing the sand:silt:clay ratios of upper Elsieskraal sediments with those of extreme lower dredged area sediments (Figure 17), also shows the similarity of these two groups of sediments. Even allowing for the superimposition of new properties during transport, it is thus probable that much of the fine material deposited in the extreme lower dredged area has its source in the upper parts of the Elsieskraal catchment. Some of this fine sediment may, however, be transported directly into the dredged area by means of wind, especially during the summer season. In some cases, fine sediments may form aggregates due to flocculation, and this will cause an increase in the rate of deposition (Westrich, 1986).

The marginally lower clay contents of the extreme lower dredged area sediments (with respect to the upper Elsieskraal sediments) is likely to be a result of winnowing (a selective removal of deposited fine material by river currents). Winnowing is also likely to produce the local variations in skewness observed within the extreme lower dredged area (Duane, 1964), although the overall fine (positive) skewness of the fine fractions of the sediments sampled in the extreme lower dredged area and the upper Elsieskraal may be due to the retention of clay-size particles between the silt grains. Such fine sediment, especially if compacted, is actually more resistant to erosion than is sand (Blatt et al, 1972). This infiltration process is particularly noticeable at the end of a long period of low flow (Reid and Frostick, 1987), and it could explain the finely skewed nature of the fine sediments of the extreme lower dredged area and the upper Elsieskraal, bearing in mind that samples were taken toward the end of the dry season.

Deposits in the extreme lower dredged area may be regarded as transitional channel fill deposits (Allen, 1965), in that although the stream carrying them has not been abandoned, the slopes and resultant flow velocities are so slight that the carrying capacity and competence of the river in this area is reduced almost to zero. Therefore, fine sediments previously held in suspension in the faster flowing lower reaches of the Elsieskraal, Vygekraal and Black Rivers are deposited in the extreme lower dredged area. This should also explain the lack of fine sediment within the

Black and Vygekraal catchments, the lower Elsieskraal catchment, and the upper, middle and lower parts of the dredged area. The anomalously high proportion of fine sediment present in sample BLA13b could possibly be due to a direct entry of additional fine material into the river at this point. The very fine mean, median and modal size values of samples BLA12a and BLA12b can also be explained in the same manner. Kurtosis is not regarded as a significant indicator of sediment provenance (McLaren, 1981; Davis, 1983).



Note: gravel and organic material omitted from calculations

Figure 17 : Plot of sand:silt:clay ratios of sediment samples from the upper Elsieskraal catchment and extreme lower dredged area

CHAPTER 6 : SAND FRACTION ANALYSIS

Particle size analyses were undertaken on the sand fractions obtained from a set of 72 watercourse sediment samples collected within the study area. Of these, subsets of 8, 17, and 14 samples represented the catchment areas of the Black, Vygekraal and Elsieskraal Rivers respectively, while a set of 33 samples from the dredged area was sub-divided into subsets of 8, 7, 6, and 12 samples, representing the upper, middle, lower and extreme lower parts of the dredged area respectively.

The sand fractions were chosen for the most extensive analysis and interpretation for the following reasons:

i. Sand comprises (by mass) some 88 % of the total quantity of alluvial material sampled within the study area.

ii. The sand fraction is that component of the sediment which is most rapidly, easily and accurately obtained by means of the preparation described in Chapter 4.

iii. Sediments within the sand size range are, for technical reasons, those best suited to particle size analysis in a settling tube.

iv. It would appear, from the literature search undertaken during this study, that relationships between sediment transport and deposition, stream power (as represented by velocity and discharge), and sediment grain size are best understood for those sediments within the sand size range.

v. The mainly quartzitic sands of the study area are unlikely to suffer any significant abrasion, chipping or grinding during transport from their supposed source areas (in the upper parts of the catchments) to the dredged area, owing to the relative hardness of quartz. In this regard, it has been shown (Pettijohn, 1975) that a typical quartz (silica) sand grain will only, on average, lose 0,01 % of its mass (or volume) for each km of river transport. Chemical alteration of quartz is also rare, due to its inert nature. Therefore, size (and shape) of grains deposited in the dredged area should be directly comparable to similar grains in the suspected source areas.

6.1 AIMS

The aims of the particle size analyses of the sand fractions are:

i. The determination of the mean, median, and modal grain sizes of these fractions, in addition to the sorting, skewness and kurtosis values of their grain size distributions.

ii. Relating these statistical parameters to sediment transport and deposition within the study area.

iii. Interpretation of trends (in the statistical parameters) within the sediments of the dredged area, in terms of indicating provenance of these deposits.

6.2 METHOD

The technical and statistical details of the settling tube apparatus, and the calculation methods (programmes) used in the particle size analyses of the sand fractions are given in Appendix 6. Therefore the procedure is only described briefly at this point. The settling tube method was initiated (at the University of Cape Town) by Flemming and Thum (1978). The system was further refined by Brink and Rogers (1985).

Sediment samples are introduced into a still, vertical water column, contained within the settling tube. As the sediment grains settle on a pan at the base of the tube, the accumulating mass is measured (at certain selected time intervals) on an accurate mass balance linked to a computer. This generates a cumulative curve, plotting accumulated sediment mass against time elapsed since the start of the settling period. Settling velocities can then also be determined from the settling times (defined by each time interval). A rather complex formula (given in Appendix 6) is used to convert settling velocity to grain size (diameter). This calculation is based on Stokes' settling law, but it also has to consider the effects of the density and viscosity of the settling medium (water) on the settling velocities of the sediment grains. For the purposes of this calculation, the diameter of each grain (at any particular point on the cumulative curve) is expressed in terms of the diameter of a sphere having the same settling velocity (the principle of hydraulic equivalence). The density (specific gravity) of the settling sediment is assumed to be 2,65 (that of quartz), since the major constituent of most sand-sized sediments is usually quartz (silica).

At the end of each settling period, the total mass collected on the pan is recorded, so that the masses collected during each time interval can be converted to percentages of the total mass. Using the calculation procedures described above, the computer (linked to the settling tube) then generates a graphical printout, plotting percentage mass against grain size (in ϕ units), showing both a cumulative and a frequency curve for each sample analysed, as well as a set of statistical graphical size distribution parameters, calculated according to the methods of Folk and Ward (1957). Mean and median grain sizes are given by the programme, as are sorting, skewness and kurtosis values. Modal grain sizes are read off the highest point of the frequency curve.

6.3 RESULTS

The results of the particle size analyses of the sand fractions of all samples are shown in tabulated form in Appendix 7. These data have also been summarized in map form in Figures 18, 19 and 20, which show mean grain size, sorting and skewness respectively. Group means for the data are given in Appendix 8, while Appendix 9 contains some selected graphical plots of the particle size analyses.

6.3.1 Mean, median and modal sizes of sand fractions

There is a significant difference between the mean grain sizes of the sediments from the Cape Flats region (the Black and Vygekraal catchments), and those from the Elsieskraal catchment (particularly its upper part). Group means for mean grain size are: Black catchment 0,91 ϕ; Vygekraal catchment 1,04 ϕ; and Elsieskraal catchment 1,65 ϕ. Mean grain sizes within the Black catchment vary from 1,47 ϕ (at sample site KRO4) to 0,17 ϕ (at sample site BLA1), while those of the Vygekraal catchment range from 1,62 ϕ (at sample site BOK3) to 0,72 ϕ (at sample site

VYG10). The generally medium to coarse nature of these sediments can be attributed to the fact that these two catchments are almost entirely covered by the silica sand typical of the Cape Flats area.

At places within the upper Elsieskraal catchment, mean grain sizes are as fine as 2,39 ϕ (at sample site ELS5), although in the lower Elsieskraal catchment, sediments are considerably coarser, with mean grain sizes ranging from 1,90 ϕ to 0,63 ϕ (at sample site ELS23). This difference in grain sizes within the same catchment may be explained by the types of soil and sand cover: in the upper Elsieskraal catchment (the Tygerberg Hills area), the fine sands are a component of the loam soils derived from the Malmesbury shales, whereas the relatively coarser sediments of the lower Elsieskraal catchment are mainly comprised of the Cape Flats silica sand cover. In the western half of the study area, there appears to be some indication of a north-south linear trend in mean grain sizes, with a belt of relatively fine sediment extending from Lansdowne to Pinelands, and a stretch of coarser sands extending from Hanover Park to Goodwood.

Within the dredged area, there is a distinct decreasing trend in mean grain size downstream, as would be expected with the decreasing river competence (the maximum grain size moved by the river) in this direction. This trend is borne out when observing the group mean grain size values: 1,06 ϕ in the upper dredged area; 1,45 ϕ in the middle dredged area; 1,67 ϕ in the lower dredged area; and 2,24 ϕ in the extreme lower dredged area. Mean grain size ranges for these areas are: 1,22 ϕ (at sample site VYG13b) to 0,88 ϕ (at sample site VYG14b), for the upper dredged area; 2,32 ϕ (at sample site VYG17d) to 1,02 ϕ (at sample site VYG16b), for the middle dredged area; 2,41 ϕ (at sample site BLA11c) to 0,97 ϕ (at sample site BLA11a), for the lower dredged area; and 2,99 ϕ (at sample site BLA16a) to 1,16 ϕ (at sample site BLA12b), for the extreme lower dredged area. There are no significant variations in mean grain size across the watercourse within either the upper or extreme lower parts of the dredged area, but a distinct decrease in mean grain size takes place northwards, across the middle and lower parts of the dredged area (Figure 18), e.g., from 0,97 ɸ (at sample site BLA11a) to 2,41 ɸ (at sample site BLA11c). Possible explanations for this belt of what might seem to be anomalously fine sediment along the northern bank of the watercourse will be discussed in section 6.4. Within the extreme lower dredged area, sediments are finer in the middle and far northern parts of this zone.

Median and modal grain sizes show very little difference from the mean grain sizes, in terms of either absolute ɸ values for individual samples, differences between group mean values, or in trends observed across the study area (or within the dredged area). This similarity in mean, median and modal grain sizes can be attributed to the generally symmetrical grain size distribution of the most of the sand fractions of the sediment samples (Davis, 1983). As a result, median and modal grain sizes are not shown in summarized map form, although they are given in Appendix 7.

6.3.2 Sorting of sand fractions

A significant difference exists between the sediments of the Black, Vygekraal and Elsieskraal catchments, with respect to their sorting. This is shown by the group mean sorting values: O,51 ɸ for the Black catchment; 0,43 ɸ for the Vygekraal catchment; and 0,59 ɸ for the Elsieskraal catchment (Appendix 8). Sediments in the upper Black catchment are very well sorted (within less than 0,35 ɸ), while those in the lower Black catchment are only moderately well sorted (between 0,50 ɸ and 0,71 ɸ). Vygekraal catchment sediments are, on the whole, well sorted (between

0,35 ϕ and 0,50 ϕ). Sorting of Elsieskraal sediments becomes better downstream, improving from only moderately sorted (between 0,71 ϕ and 1,00 ϕ) in the upper parts (the Tygerberg Hills area), to well sorted in the lower parts (around Pinelands). It would appear from these patterns, that, as in the case of mean grain size, sorting is also related to surface sand or soil cover: the loam soils of the Tygerberg area give rise to only moderately sorted sediments, whereas the Cape Flats silica sands tend to produce well sorted sediments (Hill and Theron, 1981). Most typical fluvial material is, in fact, intermediate to these two types, in that it is normally moderately well sorted (Selley, 1988).

Within the dredged area, sorting tends to become poorer downstream. While the upper, middle, and lower parts of the dredged area have mean sorting values of 0,48 ϕ, 0,50 ϕ and 0,41 ϕ (all well sorted) respectively, the extreme lower dredged area has a mean sorting value of 0,72 ϕ (moderately sorted). Within the middle and lower parts of the dredged area, sediments in the middle of the watercourse are moderately well sorted, whereas those on the south bank are well sorted. As in the case of the mean grain size, a somewhat anomalous belt of sediment is present on the north bank in these parts, the material being the only sediment within the entire dredged area that is very well sorted (Figure 19). Sediments within the extreme lower dredged area display very varied sorting values, ranging from well sorted in the middle of this zone, to poorly sorted in its northern sector. This large variation in sorting values is likely to be explained by the fact that the sediments in the extreme lower dredged area are combinations of (at least) two distinctly different grain size populations of differing origins (Selley, 1988), namely Cape Flats silica sand (from the Black and Vygekraal catchments), and Malmesbury-derived loam soils (from the Elsieskraal catchment).

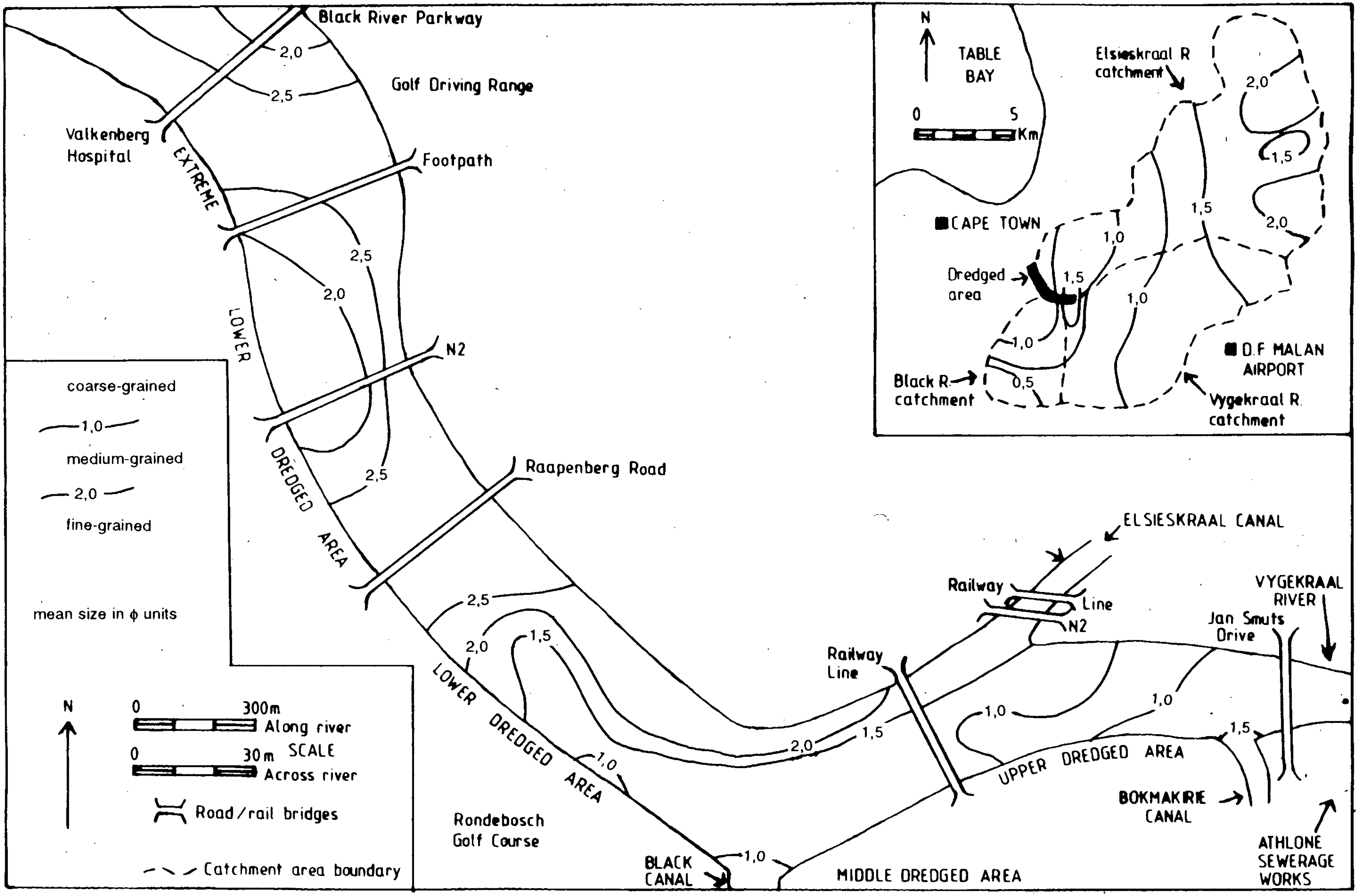


Figure 18 : Mean size of sand fraction within the dredged area (main map) and catchment areas (inset)

6.3.3 Skewness of sand fractions

All of the sand fractions of the sediment samples taken within the catchment areas of the Black, Vygekraal and Elsieskraal Rivers have either near-symmetrical (between +0,1 and -0,1) or coarse-skewed (between -0,1 and -0,3) skewness values (Figure 20). Group mean skewness values are -0,06, -0,05 and -0,14 for the Black, Vygekraal and Elsieskraal catchments respectively. Coarse (or negative) skewness values are most extreme in the upper parts of the Elsieskraal catchment, with values of -0,22 at sample sites ELS6 and ELS8. The coarse skewness of these sediments is likely to be related to their derivation from the loam soils in the area. The essentially symmetrical grain size distribution of the sediments of the Black and Vygekraal catchments is probably due to a similar distribution in the major source of material, namely the Cape Flats silica sands. Some of the sand fractions in the Rondebosch/Athlone/Pinelands area have a marked negative skewness, although the reason for this is uncertain.

Sand fractions within the dredged area display a general tendency to become more strongly negatively (coarsely) skewed downstream. This trend is indicated by the group mean values: the upper, middle and lower parts of the dredged area all show near-symmetrical values (between -0,03 and -0,09), whereas the extreme lower dredged area has a mean value of -0,16, with an extreme value of -0,55 at sample site BLA14b. Within this zone, however, there is an area of near-symmetrical sand fractions, and this coincides approximately with the area of well sorted, fine-grained sand fractions within the extreme lower dredged area referred to in sections 6.3.1 and 6.3.2. There is also, within the middle and lower parts of the dredged area, a slight trend from south to north across the watercourse, in that sand fractions on the south bank tend to be coarse-skewed, while those on the north bank are near-symmetrical (Figure 20). These near-symmetrical sediments on the north bank are present in approximately the same area as the very well sorted, fine-grained sand fractions discussed in sections 6.3.1 and 6.3.2.

6.3.4 Kurtosis of sand fractions

Kurtosis is believed by some researchers (McLaren, 1981; Davis, 1983) to be a geologically insignificant indicator of sediment provenance. Therefore, it has not been summarized in map form, although values are given in Appendix 7. With respect to the study area, however, it does show some distinct trends, in that Elsieskraal catchment sediments are more leptokurtic (group mean 1,11) than those of the Black and Vygekraal catchments, which are mainly mesokurtic (group means are 0,99 and 1,04 respectively). Within the dredged area, group mean kurtosis values increase downstream, from 1,00, 1,01 and 1,10 in the upper, middle and lower parts respectively, to 1,33 in the extreme lower dredged area (Appendix 8).

6.4 INTERPRETATION

Sediments deposited in the dredged area are likely to inherit some characteristics from their source material, although other features which were typical of the source material might be lost (or modified) during transport. Selective deposition of certain size fractions at sites between the source and the ultimate place of deposition will influence the mean size, sorting and skewness of the final deposit (McLaren, 1981), and winnowing of fine sediments out of the final deposit will further alter its nature, in terms of these parameters. Where, however, there are two (or more) distinctly different types of source material (as is the case of the Cape Flats silica sand when compared to the loam soils of the Tygerberg Hills), original features of the source materials are still likely to be recognized in the final deposits (in the dredged area). Thus, a comparison of the nature of the dredged area's sediments to those of the three catchment areas (Black, Vygekraal and Elsieskraal) could well shed some light on the origins of these deposits.

6.4.1 Types of sediment transport

Transport of alluvial material by river systems takes place in three forms (Visher, 1969), which may be best expressed in terms of three distinct sediment loads carried by a river. These are the traction load (or bedload), the saltating load, and the suspended load. The bedload usually consists of coarse material (gravel), and moves by means of rolling along the bed of the river (surface creep). Bedload movement normally occurs intermittently, during flood events. Sand is most commonly moved by means of saltation (the saltating load), which may be regarded as the bouncing of grains along the river bed (intermittent contact). This saltating material is moved continuously, but at a slower rate than that of the shear velocity of the river. The suspension load mainly comprises silt and clay, these grains remaining suspended in the water body at all times, being supported by fluid turbulence. The suspended load moves at approximately the same speed as the mean flow velocity of the river system (Allen, 1965).

In most normal fluvial sediments, where sand is the major constituent of the sediments transported by the river, the saltating load will comprise the greatest part of the total sediment quantity. This proportion usually ranges from 65 % to 98 % (by mass) of the total load (Visher, 1969). The bedload (sometimes referred to as the "coarse tail") normally constitutes less than 10 % (by mass) of the total load, whereas the suspended load (also known as the "fine tail") usually 2 % to 20 % (by mass) to the total sediment load. These proportions are, however, controlled by the grain size distribution of the sediment, and the transporting power of the river. Thus, a coarser sediment load will result in a greater bedload, whereas more fine material produces a larger proportion of suspension load; an increase in stream power will put more sediment into suspension, while a decrease is likely to result in a proportionately larger bedload. Generally, though, bedloads are usually coarser than 1 ϕ, and suspended loads are finer than 3 ϕ.

With regard to the study area, therefore, it is probable that sediment transport occurs mainly by means of saltation (as well as a possible minor bedload component) in the Black and Vygekraal catchments during the dry summer period. Owing to the additional input of fine sediment from the loam soils in its upper catchment, the Elsieskraal is, in addition to saltation load and bedload, likely to carry a suspended load, even during the dry season. During the wet winter season, an overall increase in river transporting power should lead to a general increase in suspended load, and a subsequent decrease in saltating load and bedload.

6.4.2 **Relationship between sediment transport and mean, median and modal grain sizes**

The amount of sediment that a river can transport will, to a large extent, be determined by the grain size distribution of the sediment supplied to, and subsequently transported by, the river. Although the overall rate of sediment transport by a river is most accurately determined when considering the whole grain size distribution of its sediments (Bagnold, 1968), the fact that the sediments within the study area are generally fairly well sorted means that the mean grain size alone can be used in transport rate determinations with an acceptable degree of accuracy.

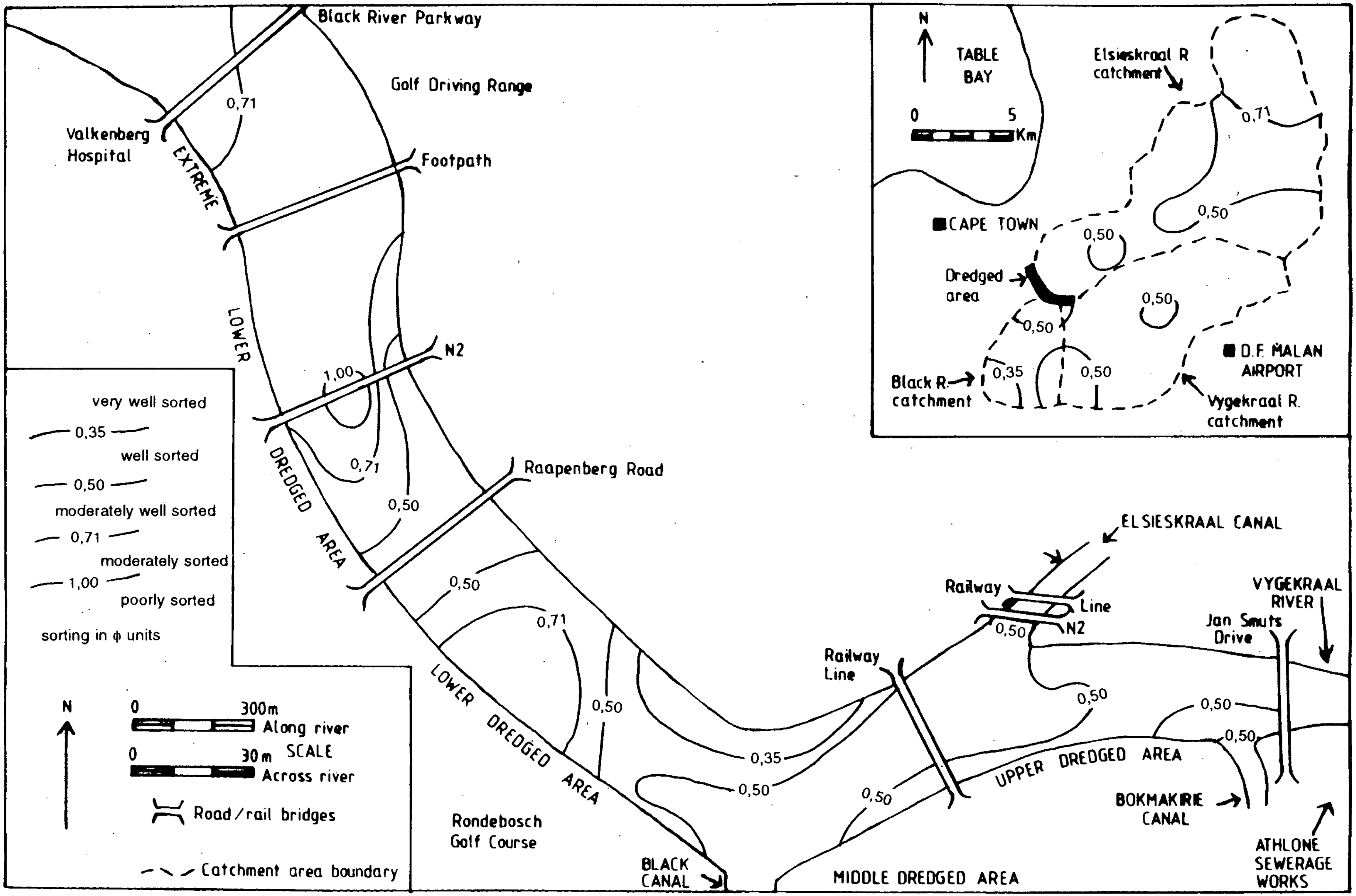


Figure 19 : Sorting of sand fraction within the dredged area (main map) and catchment areas (inset)

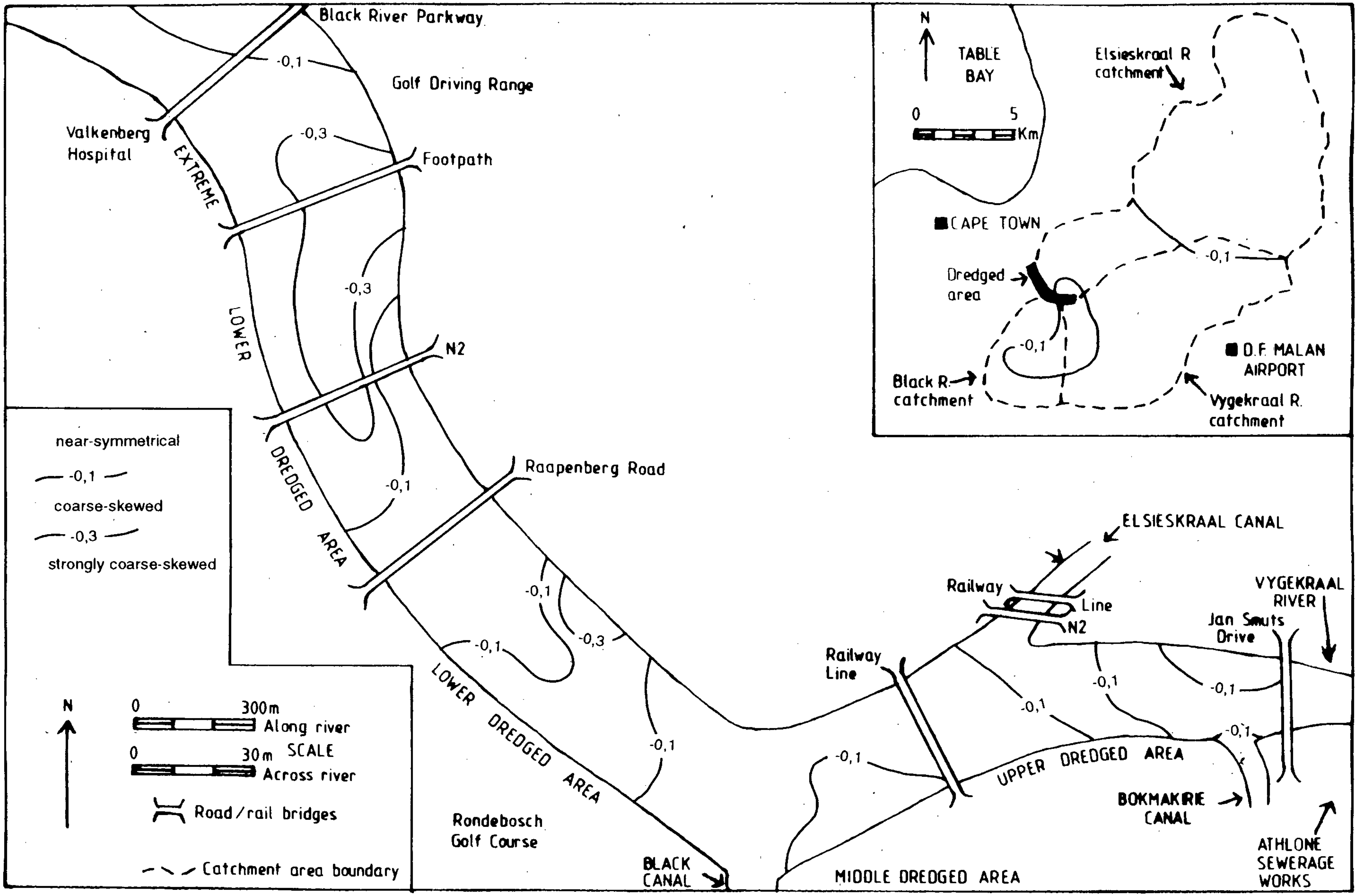


Figure 20 : Skewness of sand fraction within the dredged area (main map) and catchment areas (inset)

Sediment transport by rivers can be expressed in terms of either competence (the largest grain size that can be moved), or capacity (the maximum load that a stream can carry) (Crickmay, 1974). The question of the relative capacities of the Black, Vygekraal and Elsieskraal Rivers has, to some degree, already been dealt with in Chapter 3, but it will be further discussed in this section. The competencies of the three rivers in question will also be discussed here.

Studies undertaken by Einstein and Johnson (1950) on alluvial sediments within the sand size range (4 ϕ to -1 ϕ) showed the existence of a relationship between potential sediment transport (capacity) of saltating load and bedload, and stream discharge. This correlation is shown on the so-called "sediment function" diagram (Figure 21). For a given stream discharge, the sediment transport rate will decrease as grain size increases, since the energy (stream power) required to move coarse sand is greater than that needed to move finer sand.

Using the river discharge quantities calculated in Chapter 3, and the mean grain sizes for the sediments of the three respective catchments, potential sediment transport rates (capacities) have been estimated (Figure 21). Approximate sediment transport rates are, in tons per day:

Black:	5
Vygekraal:	20
Elsieskraal:	40

Only the discharges measured during the wet winter period were, however, great enough to be applied to the "sediment function", so the transport rates estimated by means of this method cannot be taken as representative of the whole year. In addition, it must be borne in mind that this method does not take into account the amount of sediment supplied to the rivers by their catchments. In this regard it is unlikely that the Elsieskraal is supplied with as much sediment throughout the year, as is the Vygekraal (considering the catchment area characteristics described in Chapter 2). Therefore, even if the Elsieskraal is a more efficient (or powerful) transporter of sediment during "flood" events than is the Vygekraal, it does not necessarily follow that the Elsieskraal will actually transport a greater amount of sediment than the Vygekraal, especially if the entire year is considered. The Black River would appear to be, both from the point of view of its sediment supply and its capacity, very much the minor transporter of sediments within the study area.

The so-called Hjulstrom diagram (Allen, 1965; Blatt et al, 1972; Crickmay, 1974; Pettijohn, 1975; and Selley, 1988) appears to be, from the literature research undertaken during this study, the most widely used method of determining river competence (Figure 22). This diagram shows the relationships which exist between sediment grain size, stream flow velocity, and the resultant sediment transport. It does not, however, enable the researcher to make quantitative calculations of sediment transport rates, although it is possible to obtain some idea of relative (or semi-quantitative) sediment transport, when comparing two (or more) river systems, if some measure of stream flow velocities and sediment grain size distribution are known. According to the Hjulstrom diagram, sand in the 3 ϕ to 1 ϕ size range is most readily transported by running water. For coarser sand, transport by water requires a higher threshold velocity to be exceeded, and for very fine sand, silt and clay-sized grains, a higher threshold velocity must also be exceeded, since cohesive forces between such fine grains actually increase as grain size decreases. Hence, clay (if in the form of a cohesive bed) may actually be harder to erode than coarse sand.

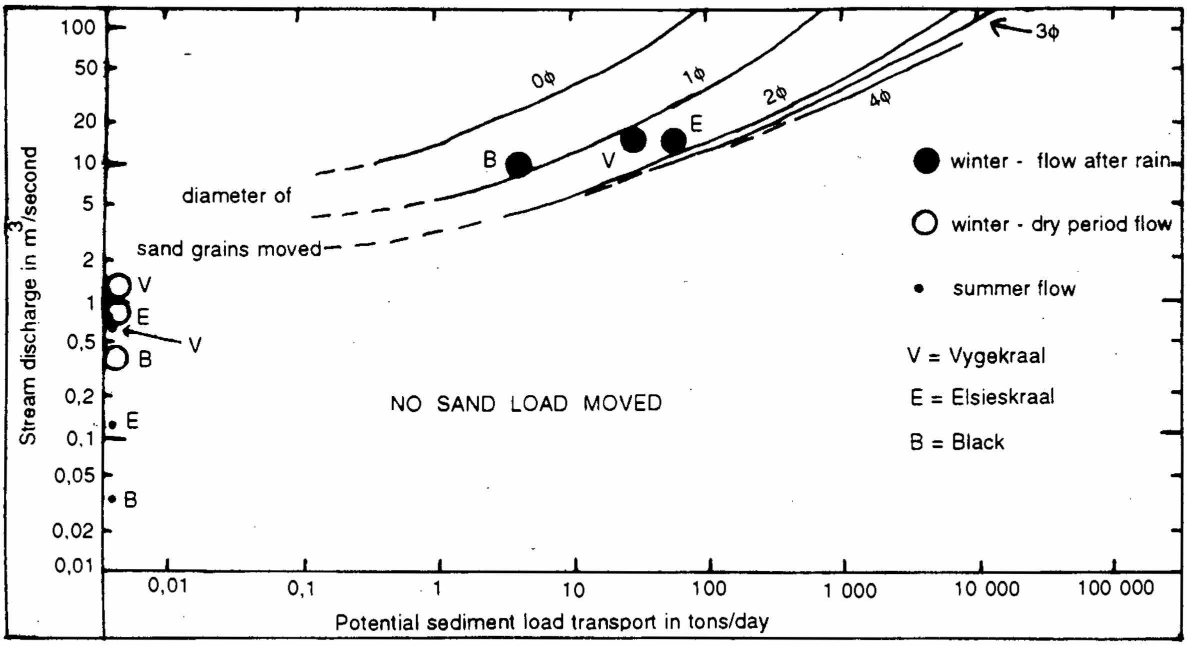


Figure 21: The 'sediment function' for river sediment load (After Einstein and Johnson, 1950)

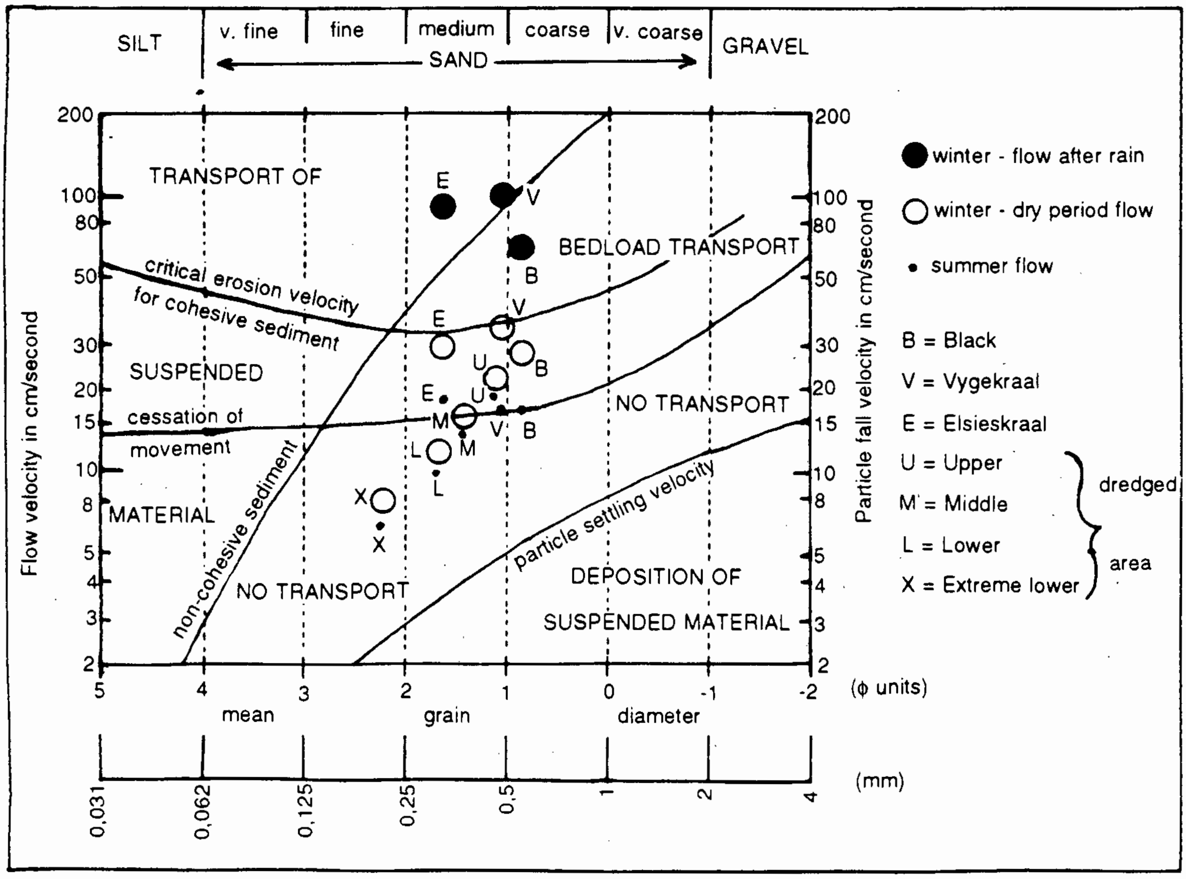


Figure 22: Hjulstrom diagram relating grain size and stream velocity to sediment transport (After Allen, 1965, and Pettijohn, 1975)

The Hjulstrom method can be regarded as being well suited to this particular study, since it is most applicable to grains of sand size (4 ϕ to -1 ϕ), and to rivers with low concentrations of suspended sediments (Allen,1965). It is also best used for flow depths of 1 m, although most of the flow depths in this study were somewhat less than that. The Hjulstrom method is based on the concept of critical velocities, which must be exceeded by the stream flow in order to initiate sediment transport. Once such a critical velocity is exceeded, the forces of turbulence and hydrodynamic lift created by the flow are sufficient to overcome the gravitational force exerted on the sediment grains, and thus the sediment is either picked up from the bed of the river, or kept in a state of suspension or saltation. In fact, there are two sets of critical velocities: a higher one, which, if exceeded, initiates transportation of stationary sediments; and a lower one, above which sediments are maintained in a state of transportation if they already were so.

In applying the data obtained in this study to the Hjulstrom diagram, the average mean grain sizes for the catchment areas and the sub-divisions of the dredged area were used, while the flow velocity referred to on the diagram is an average value of the mean flow velocity and the shear velocity (determined in Chapter 3). This intermediate value was used because the flow depths in most cases were considerably less than 1 m. These applications are shown on Figure 22.

It is evident from this diagram that sediment transport is likely to take place throughout the year within the catchment areas, and that little or no transport ever occurs within the dredged area, except for its upper part. This decrease in capacity and competence would explain the accumulation of sediments in the dredged area, assuming that all (or most) of the material transported in the catchment areas eventually reaches the dredged area. It is also apparent that suspension transport is most likely to occur in the Vygekraal and (especially) the Elsieskraal Rivers, during periods of peak flow in winter. Owing to the relative coarseness of its sediments, bedload (which includes saltation on this diagram) is the only likely form of transport by the Black River. Bedload (and saltation) transport is also likely to take place in the Vygekraal and Elsieskraal Rivers throughout the year, although summer sediment transport in all three rivers is probably intermittent, since their data for this season plot virtually on the division between transport and no transport.

Since all the data for the Black River plot closer to this dividing line, than do the corresponding data for the Vygekraal and Elsieskraal Rivers, it is probable that the capacity and competence of the Black River is significantly less than those of the Vygekraal and Elsieskraal Rivers. Using this diagram as a base, it is not really possible to say which of the Vygekraal or the Elsieskraal is likely to transport the most sediment throughout the year. Therefore from this analysis all that can be said is that most of the sediments which accumulate in the dredged area are delivered into it by the Vygekraal and Elsieskraal Rivers, with a minor contribution from the Black River.

6.4.3 Relationship between sediment transport and sorting of sediments

The sorting of the sediments within the study area, as determined by the particle size analyses, will be a function of both the hydraulic sorting capacities of the river systems (within the study area), and the size distribution of the source materials (Blatt et al, 1972). This sorting capacity will largely be determined by the flow velocities (mainly shear velocities, since most of the sediment transport in the study area is in the form of saltating load and bedload movement). In this regard, the generally moderately well sorted nature of the sediments (as represented by their sand fractions) can also be attributed to the fact that saltation is likely to be the major type of sediment transport (Visher, 1969). Local variations in sorting, as shown on Figure 19, could be the result of local changes in stream velocity, which might produce selective transport of certain sediment size ranges only.

The relatively poor sorting of the sediments in the extreme lower dredged area (as represented by their sand fractions on Figure 19), is probably due to their being a combination of (at least) two different types of source material (Selley, 1988), i.e., Cape Flats sand and Tygerberg loam. The well sorted nature of the stream sediments in the Black and Vygekraal catchments is certain to have inherited from the natural sand cover on the Cape Flats (from which fines had previously been removed by reworking, mostly by wind (Du Toit, 1984). The reworking process (by stream action) is also likely to have winnowed sediments in the Elsieskraal River (thus sorting them), and the fine material (derived originally form the loam soils on the Tygerberg Hills), which is removed would be subsequently carried downstream in suspension, to be later deposited in the extreme lower dredged area. Such sediments, winnowed free of their fine material, may be said to represent channel lag deposits (Allen, 1965). This case would apply to a lesser degree to the stream sediments in the Black and Vygekraal catchments, since the source materials within those areas do not contain a significant fine component.

6.4.4 Relationship between sediment transport and skewness of grain distributions

The coarse-skewed character of many of the watercourse sediments (as represented by their sand fractions) within the study area can, as in the case of the sorting of some sediments, be attributed to their winnowing (free of fine material) by means of stream action. This is particularly evident in the upper parts of the Elsieskraal catchment and in the extreme lower part of the dredged area (Figure 20).

The winnowing in the former area is easily accounted for by the relatively fast flowing nature of the Elsieskraal River, but the coarse skewness of the sediments in the latter area is difficult to explain, since the river capacity (as determined by its flow velocities) is very slight in this area. It is possible that the material responsible for the coarse skewness of the sediments entered the extreme lower dredged area watercourse directly (i.e., without first being transported by either of the Black, Vygekraal or Elsieskraal Rivers). Such a process would occur most probably as a result of preferential transport to the site by means of wind, or more likely via stormwater drains.

Some of the sand fractions of the sediments in the Vygekraal catchment show a slightly positive (fine) skewness, which, according to Friedman (1961) is more typical of river sands than is negative (coarse) skewness. This slight fine skewness is also present in some of the sediments of the upper and middle parts of the dredged area. This follows, since sediments in these parts of the dredged area are delivered mostly by the Vygekraal River, and therefore would be expected to retain some of the properties of their source material.

6.4.5 Relationship between sediment transport and kurtosis of grain distributions

The largely leptokurtic character of the (sand fraction) sediments within the dredged area, especially its extreme lower part, imply that part of this material achieved its sorting elsewhere in a high energy environment (such as the Cape Flats), and that it was then transported (with its size characteristic values essentially unmodified) into another environment, of lower energy and less sorting (such as the dredged area), where it was mixed with another type of material from another area (Folk and Ward, 1957). This other area could then be represented by the Tygerberg Hills and its loam soils. It would not, however, be possible (from this interpretation) to determine proportional contributions of sediment from the different catchments. Very fine sand, which may settle out from the air following transport by wind, might infiltrate the coarser sand grains, and thereby give sediments a leptokurtic size distribution (Mason and Folk, 1958).

6.4.6 Indication of sediment provenance by anomalous trends in mean grain size of the sand fraction

The belt of fine-grained, very well sorted, near-symmetrically distributed sand present on the northern bank of the watercourse within the middle and lower parts of the dredged area (referred to in section 6.3) may be the result of windblown material being deposited as "loess" in the area. The very well sorted nature of this deposit would support such an argument, since it is already known (Blatt et al, 1972; Selley, 1988) that aeolian sediments normally display very good sorting. The fine grain size of the sediment would further vindicate this suggested origin, since (owing to the vast density difference between air and sand) only fine sand (grains smaller than 2 ϕ) is usually transported by wind. According to Selley (1988), sand of the 3 ϕ size is the most easily mobilized by wind. Such wind transport of sand is very likely during the summer within the study area, owing to the abundance of dry, unconsolidated sand, and the persistent, strong southerly winds typical of that period. Once deposited in the watercourse, this fine sand is not likely to be winnowed from its place of deposition, since the flow velocities close to the river banks are virtually zero during summer, and still relatively slight even during the winter (this was observed in the field during this study). The mainly southerly direction of the summer winds in the area might also explain the presence of the fine sand deposits on the north bank, and their absence along the south bank of the watercourse (wind speeds might decrease on the windward side of the relatively high, steep banks, owing to their resistance to air flow, and thus the sediment transporting capacity of these winds will decrease, leading to deposition of the windblown material).

The presence of this belt of fine sand might also be explained in terms of relationships between stream flow velocities (as shown on the Hjulstrom diagram in section 6.4.2), and the effect of river confluences on such flow velocities, as described by Best (1987). This particular research showed that a zone of flow separation exists immediately downstream of a confluence with a tributary, and on the same side of the main watercourse, as was the tributary in question. This flow separation occurs where the tributary flow cannot remain attached to the wall of the main channel as it enters the confluence, as a result of the change in boundary geometry of the flow. Flow velocities within this separation zone may be as little as 5 % of the mean flow velocity of the main channel. If Hjulstrom's principles are applied to this situation, such a flow separation zone should be represented by sand deposits which are finer than either those in the middle of the main watercourse, or on its opposite bank. If this theory is applied to the area immediately downstream of the Vygekraal/Elsieskraal confluence, i.e., the middle and lower parts of the dredged area, then it becomes apparent that the presence of a belt of fine sand could also possibly be explained by this theory.

North-south orientated trends in the mean grain size of sand fractions of watercourse samples are present in the western part of the study area (Figure 18). These trends are probably due to preferential transport, by wind, of certain grain sizes (within the Cape Flats sand cover) in certain areas. This is likely to be reflected in the grain size distributions of the river sediments in this part of the study area, since the majority of alluvial material originates from the Cape Flats sand cover. The apparently anomalously finer belt of sediments stretching from

Lansdowne to Pinelands could result from wind transport of surface sand, from a source of finer sand within this strip. The north-south trend orientation could be explained by the dominant wind direction in the area.

CHAPTER 7 : CLAY FRACTION ANALYSIS

7.1 AIM

X-ray diffraction (XRD) analyses were performed on the clay fractions of watercourse sediment samples from the upper Elsieskraal catchment, and the extreme lower part of the dredged area, in order to:

i. determine the qualitative mineralogy of these fractions;

ii. compare the (qualitative) mineralogies of the dredged area clay fractions with those of the Elsieskraal catchment, in order to indicate a source of origin for the clays deposited within the dredged area.

7.2 METHOD

Clay fractions were obtained from those sediment samples containing sufficient material of this grain size, samples containing less than 3 % clay (by mass) not being used in this analysis. Samples analysed by XRD were: ELS3, ELS5 and ELS6 from the upper Elsieskraal catchment; and BLA12a, BLA13a, BLA13b, BLA14a, BLA15a, BLA15b, BLA16a and BLA16b from the extreme lower dredged area. The preparation of the clay fractions was described in section 4.2. Samples were analysed according to the methods outlined by Carroll (1970). Only straightforward XRD analyses were carried out on the above samples, i.e., no glycolated or oven-dried samples were analysed. The latter analyses are usually used to separate kaolinite and illite from other clay minerals (such as montmorillonite). However, according to the background literature researched as part of this study, there are no significant amounts of montmorillonite present within the loam soils of the Tygerberg Hills (which have been hypothesized as the source for the clays within the dredged area), so therefore the omission of the more elaborate XRD techniques should not detrimentally influence the results, described in section 7.3. The details of the conditions under which the analyses were performed, and of the equipment used, are given in Appendix 10.

7.3 RESULTS

The following minerals were identified in all of the samples analysed: quartz (low); halloysite ($4H_2O$ and $2H_2O$); kaolinite (1T); illite (1M); muscovite (3T and $2M_2$); and (possibly) cordierite. The presence of cordierite may not be certain in all of the samples analysed. No other minerals were readily identified. These results are summarized in Table 5, on which the 2-theta angle and the d-spacing of the peaks in diffracted radiation are shown. XRD plots of some selected representative samples are shown in Appendix 11. Since the XRD analyses carried out were basic, no interpretation can be made regarding the determination of quantitative mineral proportions within the samples from the heights of peaks on the XRD traces. Only the presence (or absence) of a particular mineral can be confirmed.

7.4 INTERPRETATION

All of the clay-size fractions qualitatively analysed by XRD apparently contain the same assemblage of minerals, namely quartz, halloysite, kaolinite, illite, muscovite and cordierite. The presence of quartz would be expected in both the source material (the upper Elsieskraal samples), and the final deposit (the extreme lower dredged area samples), since it is the most commonly occurring component in most natural sediments, and is very resistant to weathering. Kaolinite and halloysite are both known to comprise significant proportions of the suggested source material, i.e., the Tygerberg loam soils (as discussed in section 2.2), and thus their presence within the dredged area's sediments might, to some degree, substantiate the hypothesis that the clays within the dredged area are originally derived from the loam soils of the Tygerberg Hills. The presence of muscovite, illite and (possibly) cordierite in both sets of clay-size fractions should further support this concept, since all three of these minerals are also known to be present within the Tygerberg loam soils.

TABLE 5 : MINERALOGICAL INTERPRETATION OF PEAKS ON X-RAY DIFFRACTION TRACES					
2-theta angle (degrees)	d-spacing (angstroms)	observed peak height above background radiation	expected intensity of diffraction	crystal face diffracting	mineral(s) identified
8,8	10,05	high	100	001	Halloysite($4H_20$)
8,8	10,05	high	100	003	Muscovite(3T)
8,8	10,05	high	60	002	Muscovite($2M_2$)
8,8	10,05	high	80	001	Illite(1M)
12,3	7,20	high	63	001	Halloysite ($2H_20$)
12,3	7,20	high	100	001	Kaolinite(1T)
17,7	5,01	moderate	55	006	Muscovite(3T)
17,7	5,01	moderate	80	002	Illite(1M)
19,8	4,48	moderate	60	020	Illite(1M)
19,8	4,48	moderate	35	020	Kaolinite(1T)
20,8	4,27	moderate	35	100	Quartz(low)
21,4	4,15	low	35	111	Kaolinite(1T)
24,9	3,58	high	80	002	Kaolinite(1T)
26,6	3,35	high	100	009	Muscovite(3T)
26,6	3,35	high	100	003	Illite(1M)
26,6	3,35	high	100	101	Quartz(low)
29,5	3,03	low	90	421	Cordierite
35,0	2,56	low	25	112	Muscovite(3T)
36,0	2,49	low	45	200	Kaolinite(1T)
36,6	2,46	moderate	12	110	Quartz(low)
37,7	2,39	low	25	003	Kaolinite(1T)
39,5	2,34	moderate	40	202	Kaolinite(1T)
40,4	2,23	low	10	513	Cordierite
45,4	2,00	moderate	100	202	Illite(1M)

CHAPTER 8 : MICROSCOPIC STUDIES

8.1 AIM

Modal sand fractions of certain representative sediment samples were studied microscopically in order to:

i. compare and contrast the alluvial sediments from the seven sample group areas (described in section 4.1), with respect to the size distribution, shape (roundness and sphericity), and surface textures of their grains;

ii. semi-quantitatively determine the mineralogy (natural), and/or the material content (anthropogenic) of these sediments;

iii. to interpret these results in terms of indicating the origins of the watercourse sediments.

8.2 METHOD

Modal fractions were extracted from the sand fractions of 12 selected representative watercourse sediment samples. The modal values were read off the particle size analysis graphical plots for the sand fractions (presented in Appendix 9). The selected sand fraction samples were then dry sieved, within the 1 ϕ division whose mean size was closest to the actual modal size of the samples. The modal size was used in order to limit the range of grain sizes within individual samples, so as to make comparisons between the different samples more straightforward during the microscopic investigations, and to render the results of the grain point counts taken more representative (with respect to the mass proportions of minerals/substances within the samples).

Grain point counts were carried out on the modal sand fractions, which were mounted on glass slides. During the microscopic examination, a linear magnification factor of 10 (for the coarser samples), and 20 (for the finer samples), was used. A total of 100 grains were counted for each sample. Naturally occurring minerals (mainly quartz), natural substances modified for human use (mainly road aggregate and road "gravel"), man-induced substances (such as glass and concrete), and biogenic materials were identified in the samples. The grain counts have been summarized in Table 6. These same 12 samples were then photographed by means of specialized microphotographic equipment, the technical details of which are described in Appendix 12. Regarding the grain shape, only roundness is discussed, since sphericity is not so easily measured or estimated, ideally needing a three-dimensional analysis (Lindholm, 1987).

8.3 RESULTS

The grain point counts performed on the modal sand fractions are given on Table 6. Sediments of the Black River show a general decrease in grain size downstream, from a modal size of 0,20 ϕ at BLA1 (Plate 9), to 1,30 ϕ at BLA9 (Plate 10). Quartz grain contents are 76 % and 79 % respectively. In both samples, there are significant quantities of anthropogenic material, consisting mostly of road aggregate fragments (dolerite or hornfels derived from the meta-sediments of the Malmesbury Group, according to Mountain, 1990), and laterite (or ferricrete), which is frequently used as road "gravel" or cover for car parks and sidewalks in the catchment.

In contrast to the Black River sediments, alluvial material from the Vygekraal river consists almost entirely (94 % to 96 %) of quartz grains, which vary in modal size from 1,55 ϕ at VYG1 (Plate 11), to 0,75 ϕ at VYG10 (Plate 12), i.e., there is a coarsening in grain size downstream. Grains in both samples are sub-rounded to well rounded, according to the scale devised by Powers (1953) and modified by Beal and Sheppard (1956). Quartz grains from both catchments display both clear and frosted surfaces. The characteristics of the Vygekraal sediments are essentially those of their source material, the Cape Flats silica sands.

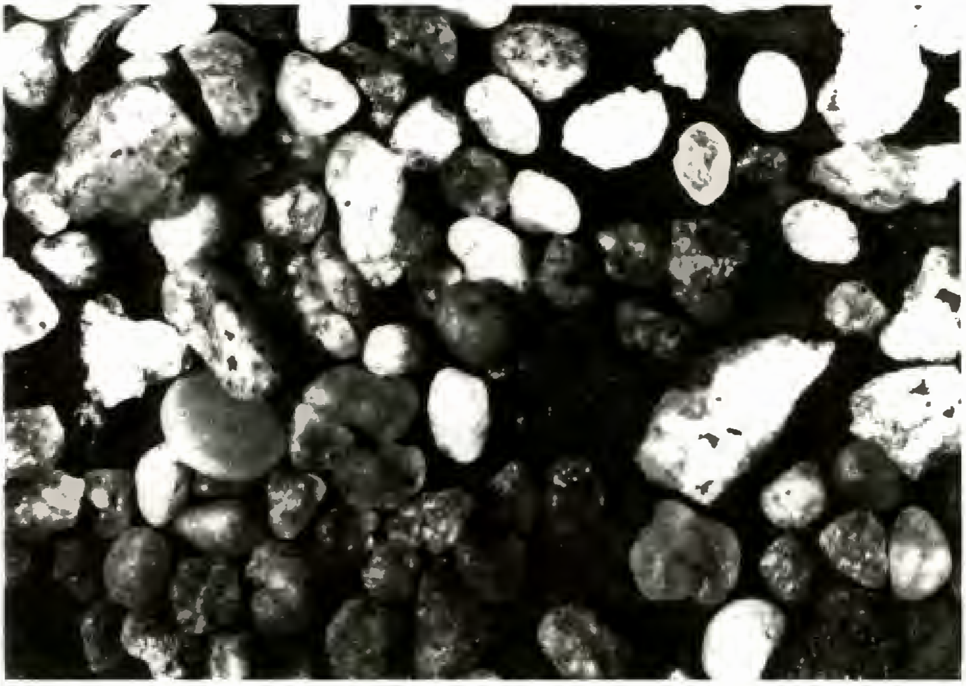


Plate 9: *BLA 1 - coarse-grained quartz sand, with fragments of road aggregate and laterite/ferricrete (linear magnification = X6)*

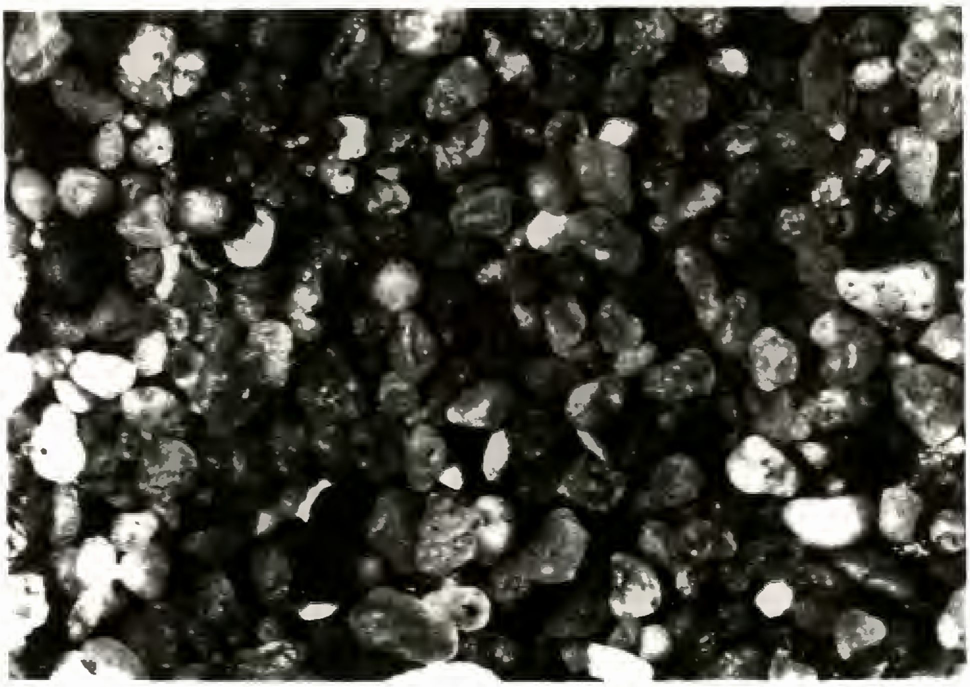


Plate 10: *BLA 9 - medium-grained quartz sand, with fragments of road aggregate and laterite/ferricrete (linear magnification = X13)*

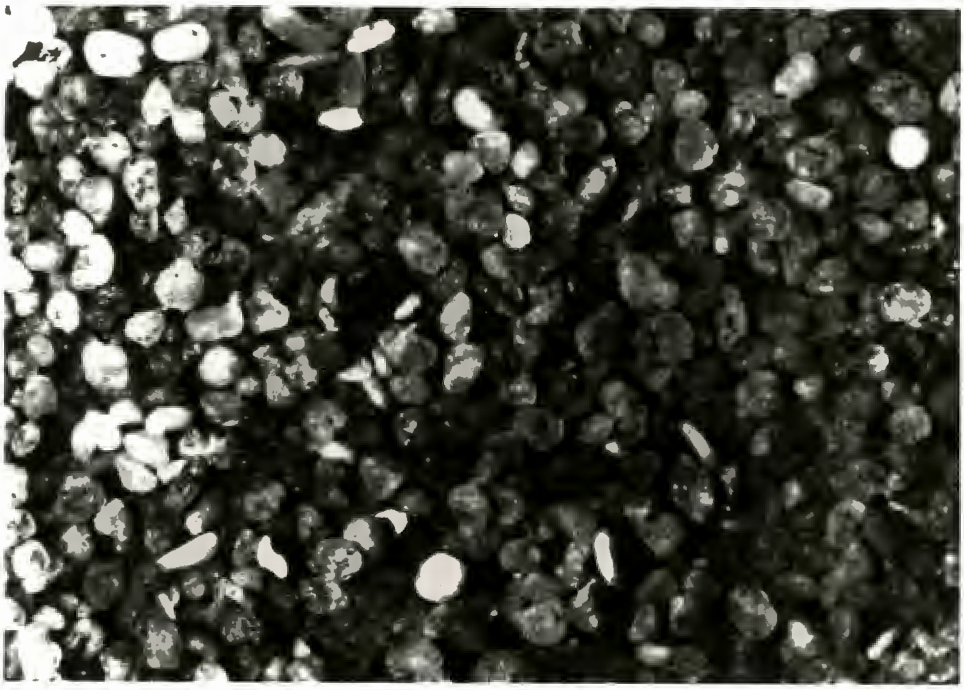


Plate 11: VYG 1 - medium-grained quartz sand (linear magnification = X16)

Plate 12: VYG 10 - coarse-grained quartz sand (linear magnification = X6)

Plate 13: ELS 3 - fine-grained quartz sand, with numerous fragments of weathered Malmesbury shale/laterite/ferricrete (linear magnification = X20)

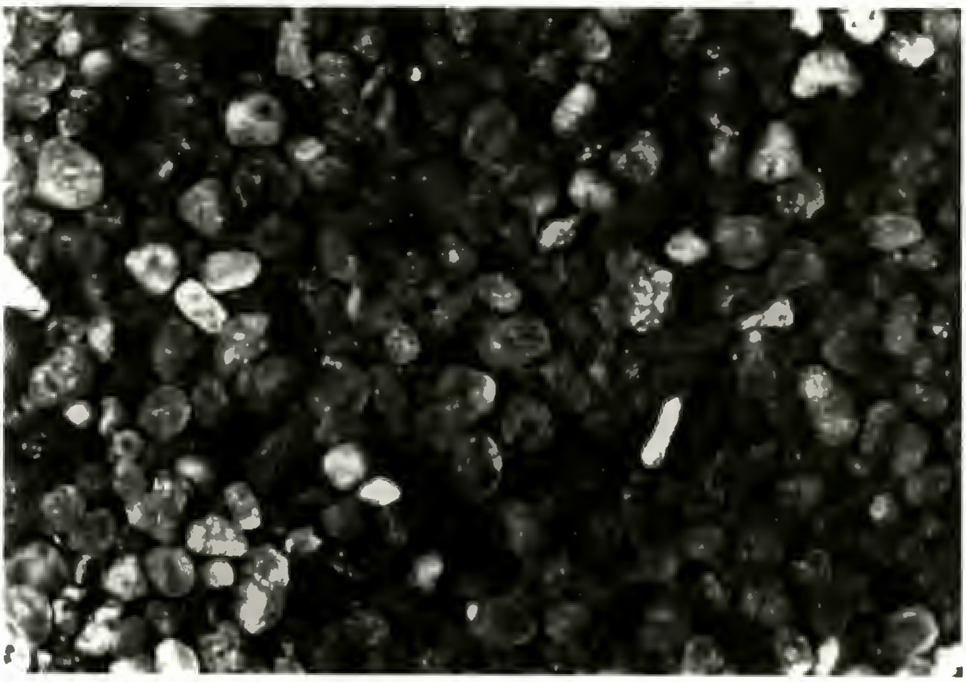


Plate 14: ELS 28 - medium-grained quartz sand, with some fragments of road aggregate and laterite/ferricrete (linear magnification = X13)

TABLE 6 : GRAIN POINT COUNTS ON WATERCOURSE SEDIMENT SAMPLES

Group	Sample	Number of grain types counted per sample					
		sand grains (quartz)	road aggregate (dolerite/ hornfels)	laterite/ ferricrete/ brick fragments/ weathered Malmesbury sediments	shell/ bone fragments	concrete fragments	glass fragments
B	BLA 1	76	12	7	1	2	2
B	BLA 9	79	9	6	3	1	2
V	VYG 1	94	2	1	2	0	1
V	VYG 10	96	1	0	1	1	1
E	ELS 3	69	3	26	0	2	0
E	ELS 28	91	5	2	1	1	0
U	VYG 15b	97	1	1	0	0	1
M	VYG 17a	97	1	0	0	0	2
L	BLA 11a	90	3	2	1	2	2
L	BLA 11c	88	8	2	0	0	2
X	BLA 12b	88	4	4	1	1	2
X	BLA 14b	90	3	3	1	0	3

Note: The above values are numbers of grains of each material counted out of a total of 100 grains per ½ ϕ division modal fraction of each sample

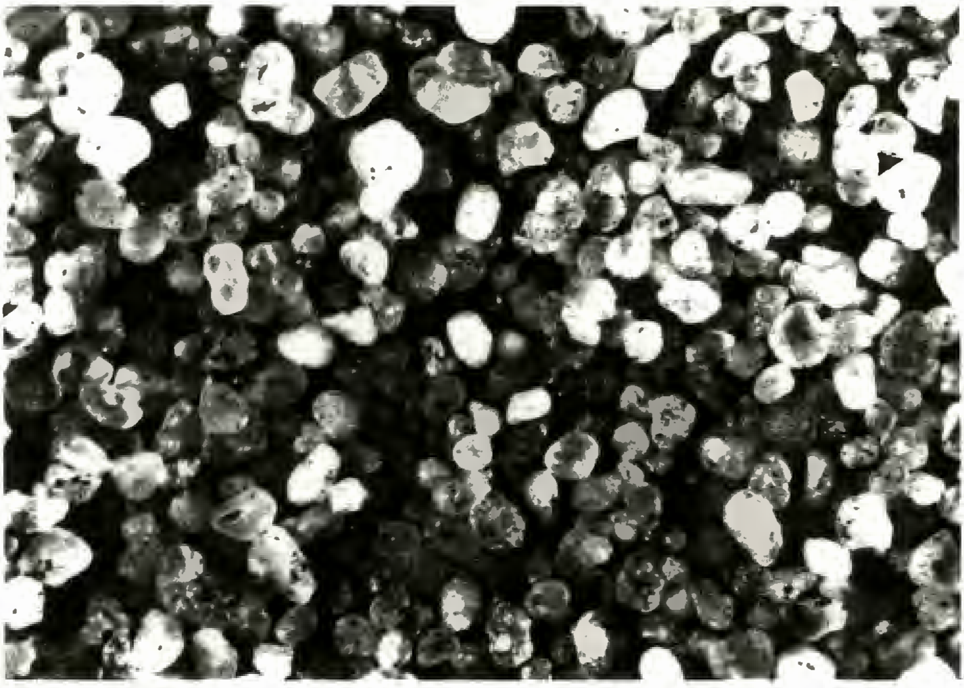


Plate 15: VYG 15b - medium-grained quartz sand (linear magnification = X10)

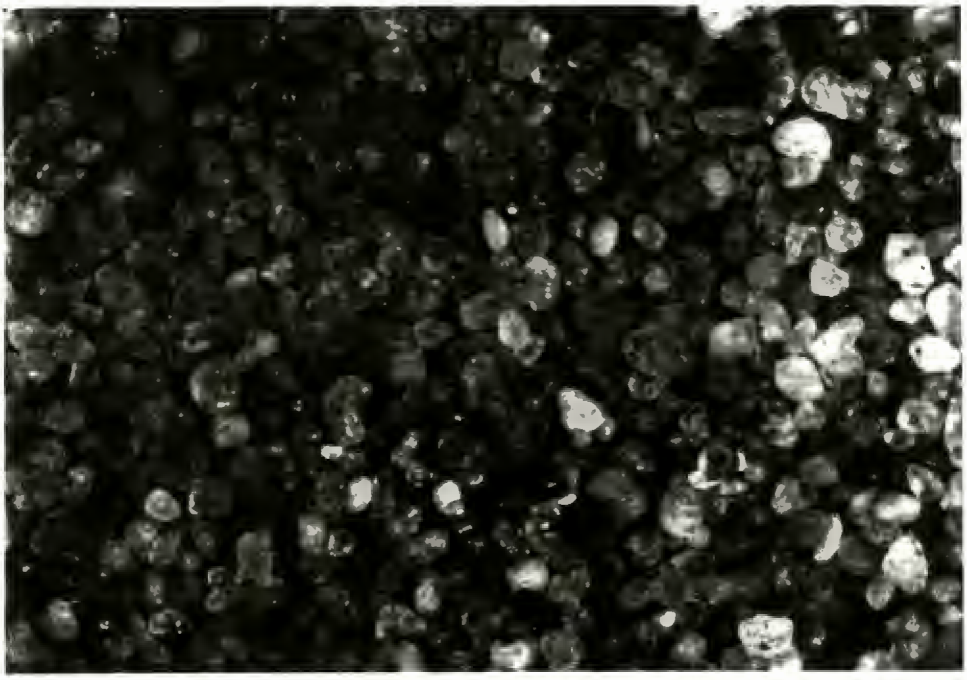


Plate 16: VYG 17a - medium-grained quartz sand (linear magnification = X13)

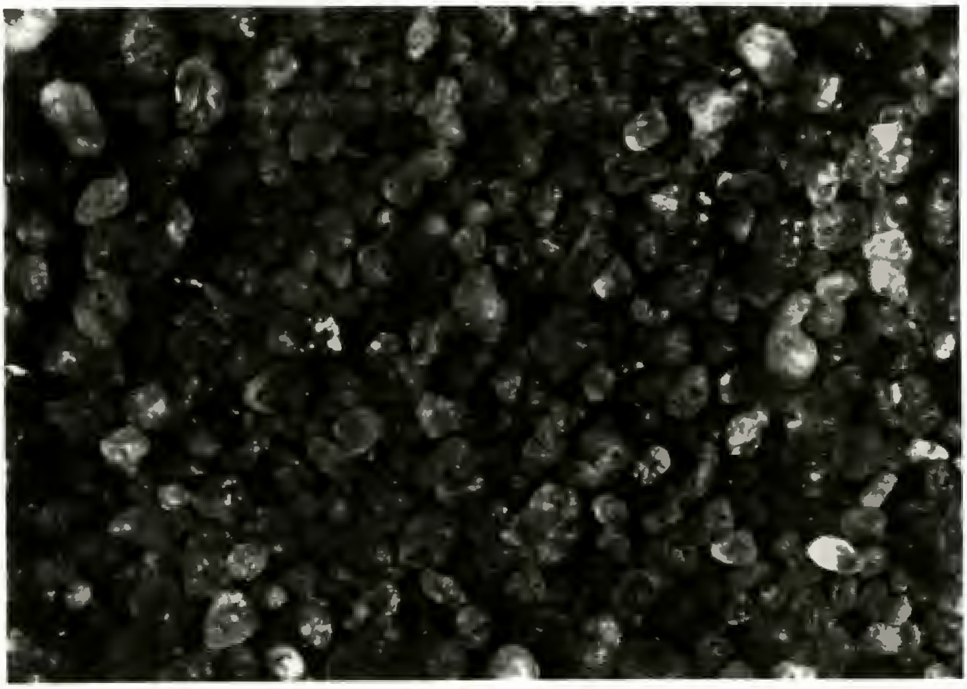


Plate 17: *BLA 11a - medium-grained quartz sand, with some fragments of road aggregate and laterite/ferricrete (linear magnification = X13)*

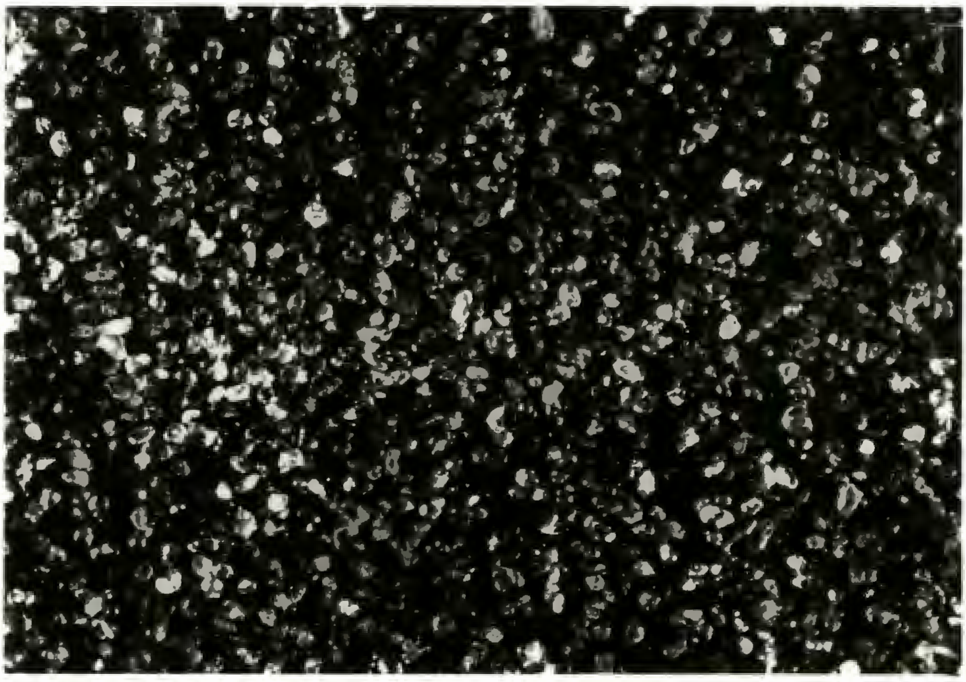


Plate 18: *BLA 11c - fine-grained quartz sand, with fragments of road aggregate and laterite/ ferricrete (linear magnification = X16)*

Plate 19: *BLA 12b - medium-grained quartz sand, with fragments of road aggregate and laterite/ ferricrete (linear magnification = X13)*

Plate 20: *BLA 14b - fine-grained quartz sand, with some fragments of road aggregate and laterite/ ferricrete (linear magnification = X20)*

Like those of the Vygekraal River, sediments in the Elsieskraal River also show a general increase in grain size downstream, from 2,30 ϕ at ELS3 (Plate 13) to 1,25 ϕ at ELS28 (Plate 14). The ELS3 sample represents a stream sediment which has been directly derived from the loam soils of the Tygerberg Hills area. This is shown by the relatively low quartz content (69 %) and the high amount of weathered fragments of Malmesbury shales (26 %). These rock fragments appear as the reddish-brown coloured grains on Plate 13. Some of these fragments may, however, be pieces of laterite or ferricrete used for road surfacing, or brick chippings. It is very difficult to distinguish between such material and weathered Malmesbury shale, since both are red or red-brown and very fine-grained. Most of the quartz grains in ELS3 are sub-angular to sub-rounded, and clear-surfaced, and are likely to have been derived from the more arenaceous Malmesbury sediments. The sediment represented in sample ELS28 contains a higher proportion of coarser, better rounded quartz grains (91 %) than does ELS3. This is almost certainly due to the inclusion of Cape Flats silica sand in the sediments of the lower Elsieskraal River. The low percentage of fine material in sample ELS28 is probably due to the winnowing discussed in Chapter 6.

Sediments in the upper dredged area (as represented by sample VYG15b on Plate 15) are very similar to those of the Vygekraal catchment, with respect to their modal grain size (1,40 ϕ) and the proportion (97 %) and shape of their quartz grains. This is to be expected, since the Vygekraal catchment is the sole source for these sediments. The middle dredged area has sediments with properties very similar to those of the upper dredged area (sample VYG17a, shown on Plate 16, has a modal grain size of 1,45 ϕ, and a quartz grain percentage of 97 %). In the lower dredged area, the decrease in grain size northwards across the watercourse (described in Chapter 6) is demonstrated by the modal grain sizes of samples BLA11a (Plate 17) and BLA11c (Plate 18), which are 1,15 ϕ and 2,40 ϕ respectively. These samples also contain a higher amount (5 % to 10 %) of road aggregate and laterite than do the sediments of the upper and middle dredged area. The sediments at sample site BLA12b (Plate 19) display a somewhat anomalous bimodality (0,70 ϕ and 1,80 ϕ) and coarser grain size, than do sediments elsewhere within the extreme lower dredged area (the coarser of the two modes is shown in the microphotograph). The sample BLA14b (Plate 20) is more typical of the majority of the extreme lower dredged area sediments, having a modal grain size of 2,25 ϕ, and a quartz grain content of 90 %.

8.4 INTERPRETATION

The overall "cleanness" (quartzitic nature and fairly good sorting) of the watercourse sediments within the study area may be attributed to the fact that such clastic sediments are the washed residues of the breakdown products of parent material (Pettijohn, 1975). The well rounded character of the quartz grains of the sediments of the Vygekraal catchment (and of their source material, the Cape Flats silica sands) is due to reworking from the quartzites of the Table Mountain Group, and possibly from the Cape Granites, i.e., the Cape Flats sands are second order sediments, so the sediments of the Vygekraal (and Black) catchments can be regarded as third order sediments. The sediments of the upper Elsieskraal River may be regarded as second order sediments, since they are directly derived from the breakdown product (the loam soils) of parent rocks (the Malmesbury Group). This fact, as well as the finer nature of their grains, is likely to explain the more angular shape of their quartz grains (Friedman and Sanders, 1978).

The downstream coarsening of the sediments of the Vygekraal and Elsieskraal rivers is more likely to be a function of the grain size distribution within the source materials, than of stream power. The very high proportion of quartz sand grains in the Vygekraal sediments is an expression of the overall type of source material within its catchment, i.e., silica sand. The northward decrease in grain size across the middle and lower parts of the dredged area may be due to either deposition of fine windblown sand, or to localized effects on stream capacity/competence resulting from the confluence of the Elsieskraal River with the Vygekraal River (this was discussed in detail in Chapter 6).

The increase in the proportions of road aggregate and laterite/weathered Malmesbury shale fragments downstream within the dredged area is probably due to the increasing relative (or proportional) contribution of the Elsieskraal River in this direction. The bimodality of the sediments in the vicinity of sample site BLA12b could either be a result of a direct entry of coarse material into this area of the watercourse, or the result of the coarse sediment carried by the upper parts of the Black River being deposited at this site due to a decrease in stream capacity.

The relatively angular, finer quartz grains which have been deposited in the extreme lower dredged area, e.g., sample site BLA14b, are likely to have originated from the upper Elsieskraal catchment, since they are very similar in size and shape to the quartz grains in sample ELS3. Such a direct comparison is possible, since abrasion of quartz is negligible in river transport (Friedman and Sanders, 1978), i.e., a quartz grain will maintain its original shape and size during such a short episode of river transport. The relatively low percentage of laterite/ferricrete/Malmesbury weathering products within the sediments of the extreme lower dredged area might be explained by the disintegration (during river transport from the source area) of such material into individual silt and clay-sized grains. Such fine, unconsolidated sediment could subsequently be transported into Table Bay, i.e. kept in suspension, even by the slow-flowing lower Black River. If this is the case, it should account for the rather low fine (non-quartz grain) content of the sediments of the extreme lower dredged area.

CHAPTER 9 : STATISTICAL ANALYSIS

The grain (particle) size analyses of the sand fractions of the watercourse sediment samples (described in Chapter 6) determined 6 variables for each sample, namely, mean grain size, median grain size, modal grain size, sorting, skewness and kurtosis. The gravel and sand proportions within each sample were earlier determined during the preparation of the sediment samples (described in Chapter 4), and the silt and clay contents of each sample were determined during the particle size analyses of the fine fractions of the sediment samples (described in Chapter 5). The 72 sediment samples have been grouped as follows, according to area:

Black River catchment (B);
Vygekraal River catchment (V);
Elsieskraal River catchment (E);
Upper dredged area (U);
Middle dredged area (M);
Lower dredged area (L);
Extreme lower dredged area (X).

Owing to time constraints and the nature of this study (in that it is only to be regarded as a pilot study), no further (more detailed) sub-divisions were made, regarding the grouping of sediment samples with respect to area. Univariate and multivariate analyses were carried out on the data set, using 72 samples and 10 variables. Programmes from the BMDP and SAS statistical software packages were used in the analyses. The univariate programmes used were a parametric analysis of variance (BMDP7D and SAS GLM), and a nonparametric analysis of variance

(BMDP3S and SAS NPAR1WAY). The multivariate analyses undertaken were parametric T-tests (BMDP3D), canonical discriminant analysis (SAS CANDISC), stepwise discriminant analysis (BMDP7M), cluster analysis (BMDP2M), factor analysis (BMDP4M), and principal component analysis (SAS PRINCOMP). Studies by Macdonald (1984) and Holmes (1987) used such techniques in order to determine the degree of distinction between different geological units on a statistical basis, and these concepts have been incorporated into this section of the research.

9.1 AIMS

9.1.1 Univariate analyses

The aim of the univariate analyses (analyses of variance) was to determine which of the 10 variables used in the data set were the most powerful discriminators between the 7 sample groups. This discriminating power was determined for the entire data set, and also for each possible group pairing.

9.1.2 Multivariate analyses

The aim of the multivariate analyses was to show the statistical differences (or similarities) between the 7 sample groups, using all 10 variables simultaneously. Particular significance was attached to the comparisons between the 3 groups representing the catchment areas (B, V and E), and the 4 groups of samples from within the dredged area (U, M, L and X), since a statistical similarity between any one of the catchment groups (B, V or E) and any one of the dredged area groups (U, M, L or X) could indicate a source of origin of the latter from the former.

9.2 METHODS

9.2.1 Univariate analyses

i. The parametric analysis of variance (BMDP7D and SAS GLM), undertaken on the entire data set, calculated a univariate F-ratio (variance between groups: variance within groups). Thus, this F-ratio increases as discrimination between groups increases. The probability of different groups representing the same population of samples is also given by the analysis, in the form of a P-value, which decreases as discrimination between groups increases. Therefore, the best discriminating variables are those with the highest F-ratios and the lowest P-values. This analysis also calculates a set of P-values for each variable in each possible group pairing.

ii. The nonparametric analysis of variance (BMDP3S and SAS NPAR1WAY) essentially performs the same tests on the data set as does the parametric analysis, the only difference being that the data is now regarded (by the programme) as not possessing a normal distribution. The output generated is the same as in the parametric analysis, i.e., a set of F-ratios (the Kruskal-Wallis test statistics) and P-values, and another set of (Mann-Whitney) P-values for each variable in each possible group pairing. Again, significant discrimination between groups is shown by high F-ratios and low P-values.

9.2.2 Multivariate analyses

i. Parametric T-tests were performed on the data set, using the programme BMDP3D. This programme, applied to normally distributed data, tests whether groups are significantly different from each other or not (BMDP manual, 1988), i.e., to test whether such groups represent the same sample population, or not. The analysis uses all 10 variables in the data set simultaneously to calculate Hotellings T^2 values and Mahalanobis D^2 values (both analogous to the F-ratios of the univariate analyses, in that the larger they are, the better is the discrimination between groups). Multivariate F-ratios and P-values are also calculated by the programme. All of these values are given for each possible group pairing. A univariate set of P-values is also generated by the analysis, for each variable in each group pairing.

ii. Canonical discriminant analysis (SAS CANDISC) was undertaken on the data set. Using all 10 variables simultaneously, this analysis generates a set of Mahalanobis distance values and P-values, similar to those of the parametric T-tests. A two-dimensional diagrammatical plot of all the sample positions (with respect to two canonical variables) is also produced by this analysis.

iii. Stepwise discriminant analysis (programme BMDP7M), was also performed on the data, and this automatically selects the most powerful discriminating variables to use in the analysis (Johnston, 1978). As in canonical discriminant analysis, a two-dimensional diagrammatical plot of all of the sample positions, as well as one showing the group mean positions, is produced against two canonical variables. Thus, it can be seen how well the sample groups are distinguished from each other. A classification matrix, comparing the pre-assigned (geographical) grouping of the samples with the grouping selected statistically by the programme, is also generated by the analysis.

iv. A cluster analysis procedure (BMDP2M) was carried out on the data set. In this technique, there is no pre-assigned grouping of samples, i.e., the analysis recognizes groups of samples objectively (BMDP manual, 1988). These samples are then plotted as points in N-dimensional space, where N is the number of variables in the data set (10 in this case). The samples are all tested together, with the so-called amalgamation distance between them being a measure of their similarity, in that the less alike the samples are, the greater is this distance. All of this information is then summarized on a dendrogram drawn by the computer.

v. Factor analysis (BMDP4M) was performed on the data. This method creates factors which represent the variables in the data set, and those variables which are correlated with each other will be loaded on one factor, while other variables which are not correlated with these are loaded on other factors. Factor 1, as determined by the programme, accounts for more variance than any of the others. As in cluster analysis, a sample is represented by a point in N-dimensional space (as defined by its factor scores). The factor scores may be regarded as a new set of variables created from the original data set, by means of re-writing common variances. Factor analysis also generates a correlation matrix for all of the variables in the data set.

vi. Principal component analysis (SAS PRINCOMP), undertaken on the data set, is a similar test to factor analysis, but differs slightly from it in that unique variances are included with common variances (SAS manual, 1985). As in factor analysis, samples are represented by points in N-dimensional space, and in this programme are plotted on a two-dimensional graph, the axes of which represent the two major principal components.

9.3 RESULTS

9.3.1 Univariate analyses

i. Parametric analysis of variance: The results from the BMDP7D and SAS GLM programmes are given in Table 7. They show that, at a confidence limit of 95 %, i.e., where P-values are less than 0,05, all of the variables (with the exception of skewness) were found to be suitable discriminators between the sample groups. Sand, silt and clay contents, modal, median and mean grain sizes, and sorting were found by the analysis to be the most powerful discriminators between sample groups. The F-ratios show the modal, median and mean grain sizes to be the most powerful discriminators between sample groups. The P-values which have been determined for each variable in each group pairing are shown in Appendix 13.

ii. Nonparametric analysis of variance: These results, from the BMDP3S and SAS NPAR1WAY programmes, are shown in Table 8. With the exception of skewness, all the other variables were found to be significant discriminators between sample groups at a confidence level of 95 %. The F-ratios obtained in the analysis show the silt and clay contents to be the most powerful discriminators between sample groups. The P-values calculated for each variable in each group pairing have been included in Appendix 14.

TABLE 7 : UNIVARIATE PARAMETRIC ANALYSIS OF VARIANCE RESULTS (BMDP7D AND SAS GLM)

Variable	Analysis of variance F-ratio	Analysis of variance P-value	Discrimination between groups
Gravel (%)	2,97	0,0127	*
Sand (%)	7,61	0,0000	***
Silt (%)	5,67	0,0000	***
Clay (%)	5,78	0,0000	***
Mode	14,99	0,0000	***
Median	13,09	0,0000	***
Mean	12,15	0,0000	***
Sorting	6,42	0,0000	***
Skewness	2,05	0,0708	---
Kurtosis	4,96	0,0003	**

Note: Mode, median, mean, sorting, skewness and kurtosis values apply only to the sand fractions of samples;
For discrimination between groups,
*** = complete
** = highly significant
* = significant
--- = not significant

TABLE 8 : UNIVARIATE NONPARAMETRIC ANALYSIS OF VARIANCE RESULTS (BMDP3S AND SAS NPAR1WAY)

Variable	Kruskal-Wallis test statistic	Kruskal-Wallis P-value	Discrimination between groups
Gravel (%)	15,36	0,0176	*
Sand (%)	37,76	0,0000	***
Silt (%)	51,06	0,0000	***
Clay (%)	51,70	0,0000	***
Mode	37,93	0,0000	***
Median	35,77	0,0000	***
Mean	35,27	0,0000	***
Sorting	18,86	0,0044	**
Skewness	11,07	0,0862	---
Kurtosis	25,59	0,0003	***

Note: Mode, median, mean, sorting, skewness and kurtosis values apply only to the sand fractions of samples;
For discrimination between groups,
*** = complete
** = highly significant
* = significant
--- = not significant

9.3.2 Multivariate analyses

i. Parametric T-tests: The results from this analysis (BMDP3D) are shown in Table 9. On the basis of these results, at a 95 % confidence level, the extreme lower dredged area was found to be distinct from all the other sample groups, with a perfect discrimination existing between it and the Vygekraal catchment area, and lesser (although still significant) discriminations between it and the Black and Elsieskraal catchments. No significant distinction could be made between the lower dredged area, and any of the catchments. The middle dredged area was distinguished from the Vygekraal and Elsieskraal catchments, but not from that of the Black. The upper dredged area was found to be significantly distinct from the Elsieskraal catchment, possibly distinct from the Vygekraal catchment, and not distinct from the Black catchment. The P-values for each variable in each group pairing are shown in Appendix 15.

ii. Canonical discriminant analysis: Results from the SAS CANDISC programme are shown in Table 10. The extreme lower dredged area is perfectly discriminated from the Black and Vygekraal catchments, and significantly distinguished from the Elsieskraal catchment. The lower and middle parts of the dredged area are not distinguished from the Black and Elsieskraal catchments, but are from the Vygekraal catchment. None of the three catchment areas are significantly distinct from the upper dredged area. These relationships between the sample groups are graphically displayed in Appendix 16.

iii. Stepwise discriminant analysis: The samples of the data set are represented as points on a two-dimensional graphical plot (Figure 23). The relative positions of the group means are shown on a similar diagram (Figure 24), with an increase in distance between group means indicating increasing discrimination between the sample groups. On the basis of this analysis (BMDP7M), the data set shows a complete distinction between the extreme lower dredged area and the Black and Vygekraal catchments, with a lesser distinction between it and the Elsieskraal catchment. The lower and middle parts of the dredged area display a similar relationship to all three catchment areas (that of partial distinction), in that their group mean positions are approximately equidistant from those of each of the three catchment areas, on the graphical plot (Figure

24). On this basis, the upper dredged area shows little or no distinction between it and the Vygekraal catchment, whereas it is significantly discriminated from both the Black and Elsieskraal catchments.

The classification matrix compiled by the programme (Table 11) shows that the classification performed by the analysis, using those variables selected by the programme as the best discriminators (sand content and modal grain size in the case of this data set) is only 47,2 % correct, with respect to the pre-assigned (geographical) grouping of samples. This shows that the overall distinction between groups is moderate, rather than good. Within the actual groups, the best classification is that of the extreme lower dredged area (66,7 %), while the least accurate is that of the lower dredged area (16,7 %).

iv. Cluster analysis (BMDP2M): The dendrogram produced by this analysis (Figure 25) does not show very clear groupings of samples, with respect to the pre-assigned grouping of samples. This is borne out by the relatively high amalgamation distances given in Table 12 (all in excess of 2 units, with the exception of the upper dredged area). This latter group has an amalgamation distance of only 1,15 units, which represents a reasonably well defined group of samples. The Vygekraal catchment (2,8 units) displays the next clearest grouping of samples, which is also indicated by the relatively large number of its samples (15 out of 17) which plot adjacent to each other on the dendrogram. The other groups are more poorly defined, with the amalgamation distance of the extreme lower dredged area group being as high as 7,7 units.

v. Factor analysis (BMDP4M): The relationships between the sample groups, as determined by this analysis, are essentially the same as those shown by the stepwise discriminant analysis. For this reason, the results of this programme are included only as appendices. Factor loadings of the variables on the factors are given in Appendix 17; factor scores for all samples are presented in Appendix 18; and a correlation matrix for the variables in the data set is given in Appendix 19.

vi. Principal component analysis: The result of this programme (SAS PRINCOMP) is essentially the same as that produced by the canonical discriminant analysis. The relationships between the sample groups are also shown to be essentially the same as those indicated by the canonical discriminant analysis, and therefore need no further discussion.

9.4 INTERPRETATION

Only the multivariate analyses provided information on the relationships between the sample groups. These analyses determine the degree of similarity (or difference) between the sample groups. If 95 % confidence limits are set on the interpretation of the data, a complete difference (discrimination) between groups, on the basis of their statistical data sets, implies that there is a chance of less than 5 % that such groups of samples represent the same sample population. On the other hand, a decrease in discrimination between groups implies that there is an increasing probability that the groups in question do represent the same sample population. A perfect correlation between groups implies (at 95 % confidence limits) that such groups have at least a 95 % probability of representing (or being derived from) the same original sample population.

TABLE 9 : MULTIVARIATE PARAMETRIC T-TEST RESULTS (BMDP3D)

Group Pairing	Hotellings T^2 value	Mahalanobis D^2 value	F-value	P-value	Discrimination between groups
B-V	20,31	3,73	2,65	0,0500	*
B-E	24,06	4,73	1,95	0,1360	---
B-U	9,63	2,41	1,03	0,4639	---
B-M	16,04	4,30	1,64	0,2514	---
B-L	18,51	5,40	1,80	0,2297	---
B-X	134,46	28,01	8,30	0,0014	**
V-E	48,55	6,32	4,60	0,0021	**
V-U	21,16	3,89	2,76	0,0442	*
V-M	29,64	5,98	3,82	0,0136	*
V-L	14,95	3,37	1,90	0,1431	---
V-X	377,91	53,72	34,99	0,0000	***
E-U	57,80	11,35	4,70	0,0070	**
E-M	48,84	10,47	3,86	0,0179	*
E-L	28,44	6,77	2,17	0,1162	---
E-X	39,99	6,19	3,54	0,0136	*
U-M	17,60	4,71	1,80	0,2152	---
U-L	15,66	4,57	1,52	0,2960	---
U-X	368,42	76,75	28,14	0,0000	***
M-L	6,99	2,16	0,64	0,7017	---
M-X	90,03	20,36	6,62	0,0037	**
L-X	77,62	19,40	5,46	0,0101	*

Note: For discrimination between groups,

*** = complete
** = highly significant
* = significant
--- = not significant

*** NOTE *** OVERLAP OF DIFFERENT GROUPS IS INDICATED BY AN ASTERISK(*).

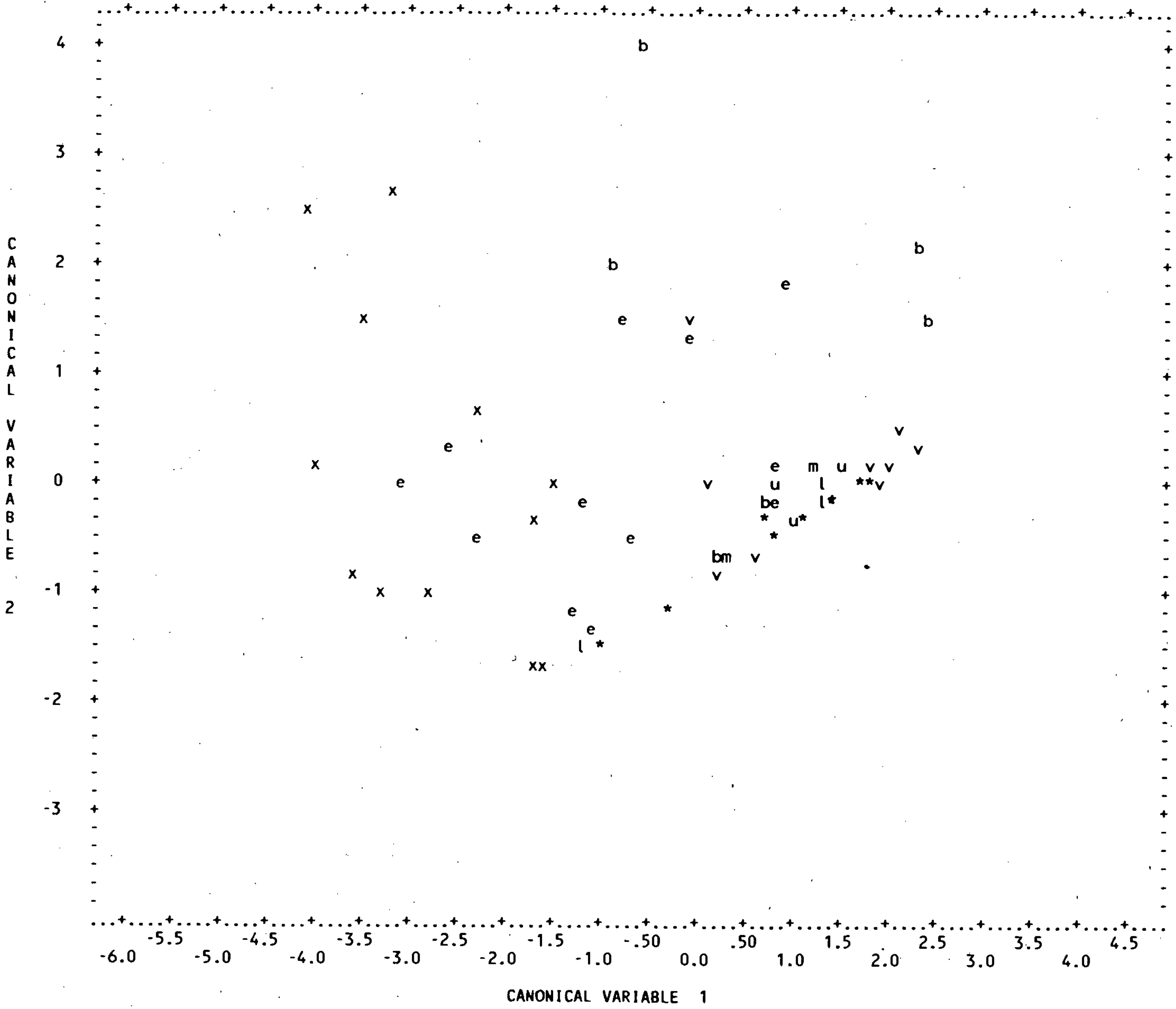


Figure 23 : Stepwise discriminant analysis (BMDP7M) - plot of all samples

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*** NOTE    *** OVERLAP OF DIFFERENT GROUPS IS INDICATED BY AN ASTERISK(*).
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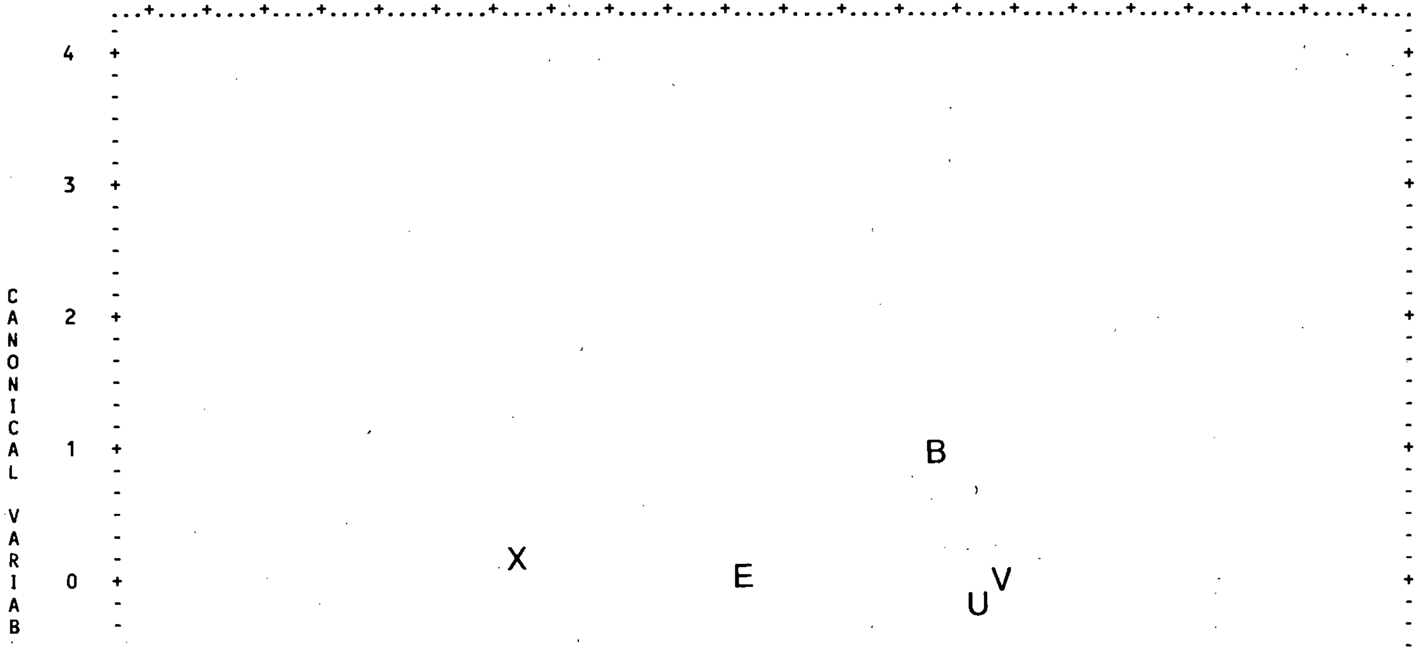


TABLE 10 : MULTIVARIATE CANONICAL DISCRIMINANT ANALYSIS RESULTS (SAS CANDISC)

Group Pairing	Mahalanobis Distance	P-value	Discrimination between groups
B-V	1,65	0,0087	**
B-E	2,06	0,0022	**
B-U	1,82	0,3522	---
B-M	2,41	0,1191	---
B-L	2,50	0,2122	---
B-X	4,38	0,0000	***
V-E	2,44	0,0000	***
V-U	0,94	0,5520	---
V-M	1,65	0,0067	**
V-L	1,81	0,0011	**
V-X	4,74	0,0000	***
E-U	2,30	0,2399	---
E-M	1,98	0,6426	---
E-L	2,10	0,7360	---
E-X	2,79	0,0007	**
U-M	1,54	0,5605	---
U-L	2,17	0,0724	---
U-X	4,82	0,0000	***
M-L	1,22	0,8939	---
M-X	4,06	0,0000	***
L-X	3,89	0,0000	***

Note: For discrimination between groups,
*** = complete
** = highly significant
* = significant
--- = not significant

TABLE 11 : MULTIVARIATE STEPWISE DISCRIMINANT ANALYSIS RESULTS (BMDP7M)

CLASSIFICATION MATRIX

Pre-assigned group	Percentage correct	Stepwise discriminant analysis classification						
		B	V	E	U	M	L	X
B	50,0	4	1	0	0	2	1	0
V	58,8	1	10	0	2	3	1	0
E	35,7	2	0	5	2	0	2	3
U	50,0	0	3	0	4	1	0	0
M	28,6	0	1	1	1	2	2	0
L	16,7	0	2	2	1	0	1	0
X	66,7	0	0	4	0	0	0	0
Total	47,2	7	17	12	10	8	7	11

TABLE 12 : MULTIVARIATE CLUSTER ANALYSIS RESULTS (BMDP2M)

Amalgamation distances for groups on dendrogram

Group	Amalgamation
B	5,469
V	2,803
E	4,855
U	1,156
M	3,935
L	3,935
X	7,720

iv. As the Elsieskraal enters the dredged area downstream of its upper part, it is unlikely to contribute any sedimentary material to the upper dredged area. Thus, all of the sediments within this area must originate from within the Vygekraal catchment, or, at least, the probability of them having done so must be very high. This is quite accurately reflected in the information produced by the SAS CANDISC programme, but is not so clearly shown by the BMDP3D analysis.

The multivariate analyses using either canonical variables, factors, or principal components (BMDP7M, BMDP4M, and SAS PRINCOMP) all show very similar relationships between the sample groups, as described in section 9.3.2. These results may be interpreted as follows, regarding the possible origins of the sediments of the dredged area:

i. Sediments within the extreme lower dredged area are most likely to have originated in the Elsieskraal catchment, and are (approximately) equally less likely to have been derived from the catchments of either the Black or the Vygekraal Rivers. These interpretations are based on the fact that while there a significant overlap between the distributions of the sample groups of the extreme lower dredged area and the Elsieskraal catchment, there is no overlap at all between the extreme lower dredged area and the catchments of the Vygekraal and Black Rivers.

ii. Within the lower part of the dredged area, the sediments are (approximately) equally likely to have originated from any of the three catchment areas, since the amount of overlap between the extreme lower dredged area and each of the three catchment area groups, as well as the distances between the positions of their means, is very similar.

iii. In the middle dredged area, sediments can only have been delivered by the Vygekraal and Elsieskraal Rivers, since the confluence with the Black is below this area. On the basis of the group distributions, there appears to be a fairly similar contribution from each of the Vygekraal and the Elsieskraal catchments.

iv. The sediments in the upper part of the dredged area can only have been supplied by the Vygekraal River. This fact is well reflected by the results from the multivariate analyses, in that the upper dredged area's sample distribution falls entirely within that of the Vygekraal catchment area, and the positions of the means of these two sample groups (as given by the BMDP7M programme) are almost coincident.

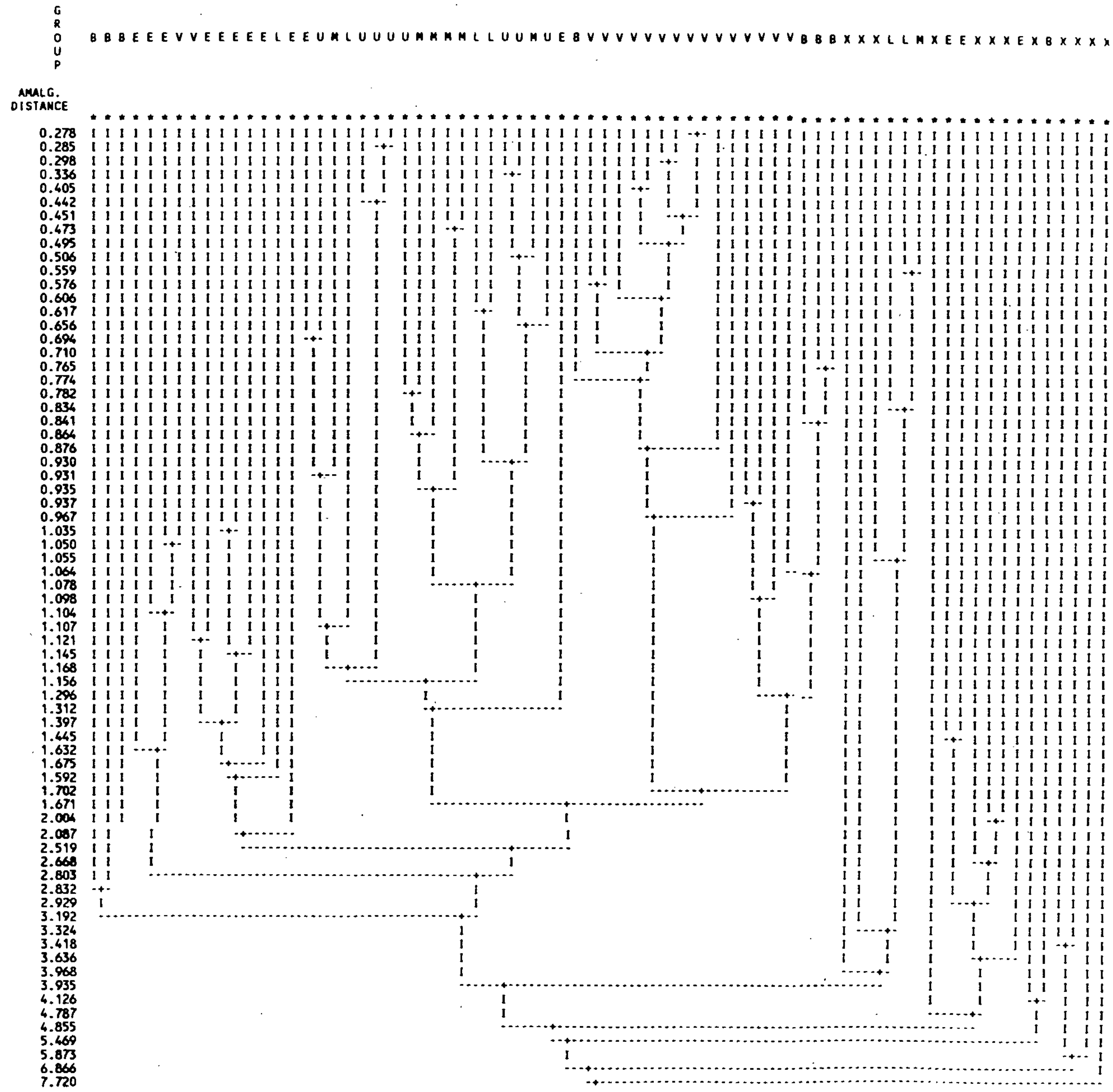


Figure 25 : Cluster analysis (BMDP2M) - dendrogram plot of all samples

CHAPTER 10 : CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

10.1 CONCLUSIONS

10.1.1 Suitability of research methodologies used

The research methodologies used in this study were, for its purposes, suitable, in that the main aims of the study were achieved in the interpretation of the results obtained. It must be borne in mind, however, that this study is only a pilot study to the research necessary to fully understand the entire system of process interactions which control soil erosion, sediment transport and deposition within the study area.

The application of measurements of stream power (in terms of discharge and shear velocity) in estimating the sediment transporting potential of the watercourses (i.e., their capacities) was vindicated by the numerous theoretical references which discussed this topic. These literature sources all showed that definite relationships exist between stream power and stream capacity. However, the actual amount of sedimentary material transported by a river (and subsequently delivered to an area of accumulation such as the dredged area) is also dependent on the quantity of sediment supplied by the catchment area. This can only be accurately determined by soil loss estimation procedures which are beyond the scope of this study. The one main factor counting against the accuracy of this section of the study in calculating the relative annual contributions of sediment from each of the three catchment areas (to the dredged area) is that flow measurements were only taken on three isolated occasions (albeit under three different weather conditions), and cannot, therefore, be regarded as being fully representative of the river flow conditions (and related sediment transport) which occur continuously throughout the year.

Owing to time constraints on this study, it was feasible only to undertake a summer sampling programme on the watercourse sediments within the study area, in which only surface grab samples were collected. This rather limited range of samples could possibly produce analytical results that are not fully representative of all the watercourse sediments within the study area. Thus, the results obtained from the various analyses (and their interpretations) should only be regarded as semi-quantitative (even where quantitative values and magnitudes are given in the results), or indicative only of approximate sediment production from the three catchment areas of the Black, Vygekraal and Elsieskraal Rivers.

The preparation of the samples (for the subsequent particle size analysis) was carried out according to accepted standard analytical procedures. Thus, the gravel, sand and fine fractions obtained could be regarded as acceptably accurate and representative of the original sediment samples. The particle size analysis performed on the fine fractions of the samples by means of the sedigraph analyser did have a disadvantage in that the entire clay component could not be fully analysed due to technical difficulties. It was possible, however, to determine the silt:clay ratios within the fine fractions.

The particle size analysis undertaken on the settling tube was regarded as being particularly suited to the research for the following reasons:

i. it is much quicker than sieve analysis, and provides a better resolution of grain size distributions;

ii. the determination of grain size distribution by means of hydraulic settling is a closer analogy to the natural sorting processes which take place in river systems;

iii. statistical parameters can be easily and quickly calculated by computer while each sample analysis is being run;

iv. the sand fractions of the sediment samples from the study area are well suited to a settling tube analysis, in the they are composed almost entirely of quartz, and have (generally) a high degree of rounding. Thus, these grains will, on the whole, be closely compatible with the assumptions made by the settling tube programme, i.e., that all settling grains are spherical and have a specific gravity of 2,65 (that of quartz).

Both of the X-ray diffraction analysis and the microscopic examinations were mainly descriptive exercises, in which samples from the dredged area were compared with those from the catchments, in order to draw some conclusions as to the origins of the sediments in the dredged area. The main assumption in doing this is that the mineralogy and grain morphology (size and shape) of the sediments does not alter significantly during transport from the catchments to the dredged area. Since most of the material comprising these sediments is either quartz, clay minerals or anthropogenic, their mineralogy (or content) should not be altered to any great degree during transportation. The fact that most of the sediments are quartz-dominated, and also that grains in the catchment areas are already fairly well rounded, means that very little change of grain size or shape should occur during transport. Thus, conclusions drawn from these comparisons (regarding the origins of the sediments in the dredged area) should be valid.

The validity of the interpretations made from the results of the multivariate statistical analyses are also dependent on there being no significant alteration of grain size during transport from the catchment areas to the dredged area. Since these analyses refer to whole grain size distributions, however, and not individual grains, it should be remembered that the grain size distributions of the dredged areas' sediments will be determined by both the grain size distribution of the source material (in the catchment area), and also by selective sorting processes during transportation. The more dominant the latter factor is in determining the final size distribution of the dredged areas' sediments, the less meaningful will be the results and interpretations made from these analyses. The fact that the two largest catchment areas possess markedly different source materials with respect to grain size, sorting and skewness (namely the Cape Flats silica sand in the Vygekraal catchment, and the Tygerberg loam soils in the upper Elsieskraal catchment) should make meaningful correlations between the sediments of the dredged area and those from the catchments (regarding the origins of the former) meaningful and valid to some degree.

10.1.2 Identification of major source areas of sediments

10.1.2.1 Interpretation of flow/discharge study results

Application of the theoretically proven relationships between stream power (discharge and shear velocity) and potential sediment transport (stream capacity) showed that the Vygekraal River had the potential to transport the most sediment throughout the year, which the Black River was likely to have the smallest capacity for sediment transport. These capacities were, however, determined by averaging the results from the three sets of measurements (summer, dry winter, wet winter), and not from a continuous monitoring of stream flows over a long period. The shear velocity calculations also indicated that the Black and Elsieskraal Rivers were likely to increase their transporting capacities under conditions of strong flow (wet winter) to a greater degree than would the Vygekraal River. The actual amount of sediment transported would, however, also be determined by the quantity of material supplied by the catchment areas (as well as by the stream capacities). Assuming that all of the sediment transported by the rivers eventually reaches the dredged area (within a year of leaving its source area), it can therefore be implied that the Vygekraal River is the major contributor of sediments to the dredged area, with the Black River delivering the least amount of sedimentary material to the dredged area.

10.1.2.2 Interpretation of particle size analysis results

A comparison of the grain size distributions of the sediments in the catchment areas with those in the dredged area, indicate that (assuming there is no significant degree of grain size alteration or preferential sorting during transport) sediments in the upper, middle and lower parts of the dredged area probably originate from the catchment of the Vygekraal River, with a likely (minor) contribution from the Elsieskraal and Black Rivers to the lower dredged area. Sediments in the extreme lower dredged area, however, are more likely to have been derived from the Elsieskraal catchment than from the Black or Vygekraal catchments (this is indicated by the mean size of the sand fractions, and the sand:silt:clay ratios of the sediments). The belt of fine, very well sorted sands on the north bank in the middle and lower parts of the dredged area could be the result of either aeolian deposits, or a reflection of a localized stream competence decrease due to the confluence of the Elsieskraal with the Vygekraal River.

Application of the theory relating grain size, stream discharge and sediment transport (stream capacity) to each other, was only possible for the wet winter condition, and showed that, under such conditions only, the Elsieskraal River was likely to have the greatest capacity for sediment transport (mainly as a result of its finer sediments). Relating stream competence (i.e., the largest grain size that can be transported) to grain size, it is apparent that sediment transport occurs all year round in the Black, Vygekraal and Elsieskraal catchment areas, and that very little sediment transport is likely to take place within the dredged area, except, perhaps, from its upper part to its middle and lower parts. This would explain the rapid rates of sediment accumulation within the middle and lower parts of the dredged area.

10.1.2.3 Interpretation of X-ray diffraction results

The results from this section of the research were qualitative only. The mineralogy of the clay fractions of the sediments in the extreme lower dredged area was found to be markedly similar to that of the clay fractions of the sediments from the upper

Elsieskraal catchment, in that a certain group of minerals (namely quartz, halloysite, kaolinite, muscovite, illite, and possibly cordierite) were found to be present in both groups of sediments. Assuming that there is no significant change in mineralogy during transportation, it can there fore be concluded that this similarity in the mineralogies of the clay fraction sediments of the extreme lower dredged area and those of the upper Elsieskraal River implies the origin of the former from the latter.

10.1.2.4 Interpretation of microscopic study results

Microscopic studies of the modal sand fractions of the watercourse sediment samples showed that while the sediments of the Vygekraal catchment area consisted almost exclusively of fairly well rounded quartz grains (directly derived from the Cape Flats silica sands), those from the Elsieskraal catchment (particularly its upper part) contained significant amounts of fragments of weathered Malmesbury shales. In addition, the quartz grains of these Elsieskraal sediments were finer and more angular than those of the Vygekraal catchment. The sediments in the Black River were found to contain greater amounts of anthropogenic materials (e.g., brick, concrete, road aggregate) than those elsewhere in the study area. In comparing these characteristics to those of the sediments in the dredged area, it seems likely that the medium-grained, well rounded, quartz-dominated sediments of the upper and middle parts of the dredged area indicate an origin from the Vygekraal catchment. The less homogeneous deposits in the lower dredged area (more variable content, grain size and grain shape) would probably reflect additional contributions from the Elsieskraal and Black catchments (to that from the Vygekraal). The fine-grained, more angular nature (as well as their variable mineralogy/content) of the sediments in the extreme lower dredged area indicate a (major) origin from the Elsieskraal catchment.

10.1.2.5 Interpretation of statistical results

The results obtained from the multivariate statistical analyses of the sediments may be interpreted as follows:

i. most of the sediments in the extreme lower dredged area were derived from the Elsieskraal catchment area;

ii. sediments in the lower dredged area are (approximately) equally likely to have been derived from any of the three catchments;

iii. sediments in the middle dredged area are most likely to originate from the Vygekraal catchment, with a possible minor contribution from the Elsieskraal catchment;

iv. the fact that the sediments in the upper dredged area could only have been derived from the Vygekraal catchment is vindicated by results of the multivariate analyses.

10.1.2.6 Conclusion

The calculation of the relative sediment transporting powers of the Vygekraal, Elsieskraal and Black Rivers shows that, over a period of one year, the Vygekraal

River is likely to introduce the greatest amount of sediment to the dredged area, with the Black River contributing the smallest quantity of sediment to the dredged area.

Particle size analyses of the stream sediments indicate that the major source of the sediments which accumulate in the upper, middle and lower parts of the dredged area lies within the Vygekraal River catchment. Particle size analysis, and an X-ray diffraction study of the mineralogy of the clay fraction, both show that the sediments deposited in the extreme lower dredged area are most likely to have originated in the Elsieskraal River catchment.

A microscopic study of the sand fraction and a statistical analysis of the particle size distribution of the sediments show that sediments in the upper half of the dredged area mostly originated from the catchment of the Vygekraal River, with the proportional contribution from the Elsieskraal River increasing downstream in the lower half of the dredged area. The quantity of material delivered by the Black River to the dredged area is, on the basis of these studies, negligible with respect to the total amount of sediment transported to the dredged area.

The land use patterns, nature of surface cover and environmental elements present within the study area, indicate that the areas most vulnerable to soil erosion are situated within the Vygekraal River catchment on the Cape Flats. Other areas which are also susceptible to soil erosion (although to a more limited extent) are present within the Tygerberg Hills region north of Bellville, in the upper Elsieskraal River catchment.

10.2 RECOMMENDATIONS FOR FURTHER RESEARCH

It has already been stated that this study should be regarded only as a pilot study towards further research on soil erosion, fluvial systems, sediment transport and deposition within the study area. Such additional research might be able to provide accurate quantitative information on sediment yields within the three catchment areas of the Black, Vygekraal and Elsieskraal Rivers, as well as indicating (with a greater degree of certainty than in this study) the precise areas of origin of the sediments that are accumulating annually within the dredged area. Any further research should study the cause of the problem (soil erosion), and its effect (sediment transportation and deposition).

10.2.1 Further research into soil erosion in catchment areas

10.2.1.1 Application of soil loss estimation models

In order to be able to accurately determine the amount of sediment being transported by the Black, Vygekraal and Elsieskraal Rivers, the quantity of sediment produced annually within each of these catchment areas must be calculated. The most feasible method of accomplishing such a task would be to apply a soil loss estimation model to each of the three catchment areas.

The best known of these models is the Soil Loss Estimation System for Southern Africa (SLEMSA), devised by Ellwell (1977). Such a model is thought by researchers to be a relatively inexpensive and easily applicable technique for quantifying soil losses (Hudson, 1987). There are, however, a number of problems with using this type of model in the study area. These are:

i. SLEMSA was designed specifically to predict soil losses from sheet erosion only;

ii. SLEMSA was originally devised for use in agricultural areas within the summer rainfall region;

iii. SLEMSA only considers seasonal rainfall energy as a climate-related cause of soil erosion (Boddington, 1980).

Thus, if a SLEMSA-type model is to be used in order to calculate soil loss or sediment yield within the catchment areas, it would need to be modified to consider other possible types of soil erosion, the effects of urbanization, and the transporting energy provided by wind (particularly during the dry Cape summer).

Soil erosion is controlled and determined by a complex interaction of variables, all of which would have to be quantitatively related to the estimated soil loss. These variables are: seasonal rainfall energy; seasonal wind energy; percentage effective vegetative cover; soil erodibility (susceptibility to erosive forces); slope steepness; and slope length (Baver et al, 1972). Since the type of land use will be likely to determine vegetative cover and soil erodibility, this factor should also be taken into account when estimating soil losses. In fact, a number of sub-models, each representing a different type of land use, would have to be employed within each catchment area. From these, an overall figure could possibly be determined for soil loss within each catchment. Rates of surface lowering (denudation) within known catchment areas could also used to determine sediment yield from such areas (Le Roux, 1990).

10.2.1.2 Investigations into measures to alleviate soil erosion

Measures to control or minimize soil loss within the catchment areas could be further studied. The most effective results in either halting or controlling soil erosion are usually achieved by increasing the effective vegetative cover in areas vulnerable to soil erosion. This can be accomplished either by the planting of grasses, or by cultivating various hardy species of plants in susceptible areas. Research could also be undertaken on the effectiveness of windbreaks (vegetative arrays) in minimizing wind erosion (Liu et al, 1990). Urban planners can, in addition, assist in controlling soil erosion, by prohibiting development on very steep slopes, e.g., slopes having a gradient of greater than 1 in 6 (16,7 %).

10.2.2 **Further research into sediment transport and deposition**

10.2.2.1 Studies of the sediments' characteristics

Further investigations into the characteristics of the watercourse sediments within the study area may possibly shed more light on their likely origins. Comparisons could be made between the sediments in the catchment areas and those in the dredged area, in terms of their properties, in order to determine (perhaps with more certainty than in this study) their probable origins.

Further particle size analyses might be undertaken on sediments collected at different times of the year, and from differing depths (i.e., using coring or auguring techniques) in order to establish any variations (if they exist) in sediment properties with either season or depth. It is possible that depth, or the position of a sample with respect to a bedform, might influence the grain size distribution of a sediment

(Love et al, 1987). Heavy metal contents (Taljard, 1984) and geochemical properties (Willis, 1979; Hatherly and Viewing, 1982) of the sediments could be investigated as indicators of their origin (provenance). Since quartz is the most commonly occurring mineral within the study area, scanning electron microscopy might be undertaken on the sediments in order to suggest possible origins on the basis of the quartz grains' surface textures (Krinsley and Doornkamp, 1973). A multivariate statistical analysis programme, based on that performed in this study, could be further expanded by a more detailed sub-division of the study area into more smaller sub-catchments, thereby increasing the size of the data set. More variables, such as those obtained from geochemical analysis, could be used in the statistical analyses, so as to (hopefully) increase the distinction between sample groups.

10.2.2.2 Specific sediment transport studies

This category might be further divided into transport of sediment by water, and transport of sediment by wind. Wind-induced soil mobilization and sediment transport has not been discussed in any detail in this study, since it was beyond the scope of the thesis. Wind transport does, however, play a significant role in sediment transport within the study area, particularly in the dry summer months, and as such, it should be studied further. It has been proved by previous research that sand in fine- to medium size range (3 ϕ to 1 ϕ) is most easily moved by wind, especially if it is dry, well sorted and contains little silt or clay (Hallward, 1988). Such sand is typical of the Quaternary cover on the Cape Flats.

Sediment transport by water might be studied by two methods:

i. By means of measuring stream power (discharges; shear velocities), and subsequently calculating the stream capacities using the applied stream power approach suggested by Rooseboom (1986). The most meaningful and accurate measurements made of stream power would be those monitored on a continuous basis (Ninham Shand, 1979; Ninham Shand, 1983), over a certain length of time, e.g., one year. River flows (discharges) could also be calculated by means of mass balance equations (Pitt, 1987). Run-off (which will determine river flows) could also be monitored in areas susceptible to soil erosion, and, in doing so, might be related to rainfall (Simpson and Kemp, 1982). Relationships between run-off and the type of land use exist, and these might also be studied further.

ii. By means of the actual measurement of the quantity and rate of sediment transport by watercourses. Such measurements could be carried out by using sediment traps at suitable positions (Lewin, 1981), with further allowances being made for stream bed width. Sediment traps could consist either of pit traps across the stream bed, or of baskets/pans lowered onto the bed. These traps would only really measure the bed load and saltating load of the sediment transported by a river. It would be advisable, therefore, to also employ a method by which the suspended load might be measured (Shen, 1978; Christiansen, 1986; Renger, 1986), in terms of its transport rate. Relationships between the sediment supply within a particular catchment area (a function of soil loss), and sediment delivery by its watercourses (a function of stream power) might also be investigated (Banasik, 1986), in order to possibly predict the delivery of sediments to regions of accumulation such as the dredged area. Relationships between land use (or the degree of urbanization) and sediment transport rates by rivers within the relevant areas could, perhaps, also be studied further.

10.2.2.3 *Use of tracers to determine origin of sediments*

The use of tracer substances, consisting either of radioactive materials or of stable isotopes, might be investigated as a means of determining rates of erosion in the catchment areas, and/or measuring sediment transport rates by watercourses (Atomic Energy Corp., pers. comm.). Such tracer tests could be undertaken for several sub-catchments, or micro-drainage areas, within a larger catchment area. Tracer tests should be performed in both winter and summer, so as to provide information on relative wind- and water-induced soil erosion and sediment transport rates. If such tests are to be used in later research, it would, perhaps, be best to initially conduct a feasibility (or pilot) study. Suggestions have been made as to how this might be carried out (Atomic Energy Corp., pers. comm.).

10.2.3 **River management**

Correct river management procedures will assist in minimizing the detrimental effects of increasing urbanization on the watercourses within a developed (or developing) area. Measures that will lead to an alleviation of soil erosion may be seen as an important part of a river management programme. Such measures will include landscaping of areas adjacent to rivers or canals (Beaumont, 1986), and a strict control on construction works near watercourses to ensure a minimum amount of soil disturbance (Anderson, 1989). Appropriate stormwater techniques, too, can assist in the avoiding of potential problems associated with stormwater (and therefore the watercourses into which these drains flow) in newly developing areas (Wiseman, 1990). Flood control in stormwater drainage networks and their associated watercourses might be studied further (Ferguson, 1990) since flood events (during which abnormal amounts of sediment are washed downstream) are invariably followed by periods of excessive deposition, particularly in sections of watercourse with low carrying capacities, such as the dredged area.

10.3 CONCLUDING SUMMARY

The research undertaken in this study has shown that the catchment area of the Vygekraal River contributes the greatest proportion to the total amount of sedimentary material which enters, and accumulates in, the dredged area. The Elsieskraal River is shown to introduce an intermediate amount of sediment to the dredged area, while the Black River transports the least amount of sediment.

This study is only a pilot study to research necessary to fully comprehend the interactions between soil erosion, sediment transport and deposition within the study area. More detailed sediment sampling programmes and sediment transport studies would have to be undertaken in order to accurately determine the percentage contribution of each catchment area to the total quantity of sediment accumulating in the dredged area. The use of tracers should also be employed in order to identify source areas.

Soil loss estimation models, suitable to the environment of the study area, might be applied in order to estimate the amounts of sediment removed annually from each catchment area. Further investigations into measures to alleviate soil erosion in the study area could be undertaken, since a decrease in soil loss within the catchments of the Vygekraal, Elsieskraal and Black Rivers will result in less sediment accumulating in the dredged area.

APPENDIX 1: PREPARATION OF WATERCOURSE SEDIMENT SAMPLES

1. All samples were oven-dried at 40°C (12 to 18 hours), and then gently crushed with a mortar and pestle, in order to:

   a) expel moisture;
   b) separate aggregates as far as possible, while not breaking grains.

2. All samples were then weighed off at exactly 50 g.

3. All these 50 g samples were then sieved by hand (at ½ ϕ intervals between -1 ϕ (2 mm) and 4 ϕ (0,0625 mm)), so as to:

   a) eliminate gravel;
   b) remove fine material (silt and clay);
   c) retain the sand fraction.

4. The mass percentage fractions of each grain size class in each sample were then obtained by weighing on a balance, as such:

   a) gravel (coarser than -1 ϕ);
   b) sand (between 4 ϕ and -1 ϕ);
   c) fine material (finer than 4 ϕ).

   These divisions follow the Udden-Wentworth scale for size classification of sediment grains.

5. Excess sample material remaining after the 50g weigh-off (from all the original dried crushed samples) was then immersed in water, agitated, and left to settle in order to determine (approximately) the organic content of the samples (the organic content, being less dense than the inorganic sediments, should either float to the surface or settle out at a slower rate than the sediments).

6. Many of the samples were, by the above method, determined as containing negligible organic matter.

7. These same samples were, by means of the method outlined in (4), also found to have a negligible fine material content.

8. The above samples ,i.e., those mentioned in (6) and (7) as having negligible amounts of either fine or organic material, were from this point onwards assumed to have a zero fine content and a zero organic content. These samples were:
   BLA: 1,3,5,7,9;
   KRO: 1,4,6;
   VYG: 1,3,5,7,9,10,12;
   BLO: 2,4,5,6;
   BOK: 1,3;
   JAK: 1,3;
   KAL: 2,3;
   ELS: 13,14,17,19,23,25,28,29;
   VYG: 13a,13b,14a,14b,14c,15a,15b,15c;
   VYG: 16a,16b,16c,17a,17b,17c,17d;
   BLA: 10a,10b,10c,11a,11b,11c.

These samples were not deflocculated, wet-sieved, or treated with hydrogen peroxide in the later stages of the analyses.

9. The sand fractions of the above-mentioned samples were then split randomly (using a mechanical splitter) to obtain a sample with a mass between 2 g and 4 g. These split samples were later analyzed for particle size distribution in a settling tube.

10. The remainder of the samples, i.e.,

    ELS: 3,5,6,8,9,11; and
    BLA: 12a,12b,12c,13a,13b,14a,14b,14c,15a,15b,16a,16b;

    were then again oven-dried at 40°C overnight (12 to 18 hours).

11. Exactly 20 g was then weighed off from each of these samples.

12. A one litre solution containing 35,7 g of the deflocculating agent $Na(PO_3)_6$ (Calgon), and 7,9 g of Na_2CO_3, was then made up.

13. 20 ml of this solution (as well as 50 ml of water) was then added to each weighed-off 20 g sample.

14. These samples were then shaken mechanically overnight (12 to 18 hours) in order to disperse aggregates of sediment grains.

15. Once dispersed, the samples were then wet-sieved separately at 4 ϕ (0,0625 mm) for 15 to 20 minutes, to separate the sand fractions from the fine fractions (silt and clay).

16. Each entire sand fraction was retained in the sieve (after each wet-sieving), and retrieved into beakers (one for each sample). Most (but not all) of each fine fraction was captured in beakers (one for each sample) under the sieve during the wet-sieving.

17. The sand fractions were then oven-dried at 40°C overnight (12 to 18 hours).

18. The sand fractions were then weighed on a balance, to determine their % mass (of each original whole sample).

19. The % masses of the fine fractions were thus obtained by subtraction.

20. Both the sand fraction and the fine fraction of each sample were then treated (oxidized) with 20 ml of 30 % hydrogen peroxide and 100 ml of 6 % hydrogen peroxide: the samples were heated at 40°C for one hour, being stirred occasionally, and then brought briefly to the boil (at 100°C).

21. The oxidized sand fractions were then washed, and oven-dried at 40°C overnight (12 to 18 hours).

22. The dry oxidized sand fractions were then weighed to determine the % mass lost during oxidation, i.e., the % mass lost due to removal of organic matter from the sand fractions of the samples.

23. Assumptions made at this point were:

    a) the ratio of organic matter:inorganic sediment was the same in the sand fraction as in the fine fraction (since it was not possible to retrieve all of the fine fraction during wet-sieving);

b) gravel fractions (removed prior to wet-sieving) contained no organic matter.

24. Thus, a total organic % mass (sand fraction organics % plus fine fraction organics %) was calculated for each sample.

25. The treated sand fractions were then split randomly (in a mechanical splitter) in order to obtain a sample of mass between 2 g and 4 g, later to be analyzed for particle size distribution in a settling tube.

26. The treated fine fractions were kept wet (and in suspension), so that they could later be analyzed for particle size distribution in an analyzer (sedigraph). This particle size analysis would also determine the silt:clay ratio within the fine fractions.

APPENDIX 2: DETAILS OF THE SEDIGRAPH PARTICLE SIZE ANALYSER

Type:	Micrometrics sedigraph particle size analyser.
Settling liquid:	Calgon ($Na(PO_3)_6$) at 28°C to 30°C.
Assumed density of settling grains:	2,65 g/cm^3 (specific gravity of quartz).
Assumed shape of settling grains:	Spherical.
Calculator:	Desk-top Hewlett Packard 9830A.
Program:	HP-BASIC.
Reading intervals (mass):	0,1 ϕ interval.

Formulae used to determine grain size from grain settling velocity, and graphical statistical parameters from particle size distribution are the same as those used with the settling tube.

APPENDIX 3: RESULTS OF PRELIMINARY PARTICLE SIZE ANALYSIS OF ALL SEDIMENT SAMPLES

Group	Sample	% Gravel	% Sand	% Silt	% Clay	% Organics
				(determined on sedigraph)		
B	BLA 1	24,04	75,96	0,00	0,00	0,00
B	BLA 3	5,50	94,50	0,00	0,00	0,00
B	BLA 5	0,53	99,47	0,00	0,00	0,00
B	BLA 7	67,30	32,70	0,00	0,00	0,00
B	BLA 9	42,66	57,34	0,00	0,00	0,00
B	KRO 1	15,69	84,31	0,00	0,00	0,00
B	KRO 4	1,28	98,72	0,00	0,00	0,00
B	KRO 6	2,56	97,44	0,00	0,00	0,00
V	VYG 1	0,00	100,00	0,00	0,00	0,00
V	VYG 3	0,98	99,02	0,00	0,00	0,00
V	VYG 5	0,00	100,00	0,00	0,00	0,00
V	VYG 7	0,00	100,00	0,00	0,00	0,00
V	VYG 9	0,96	99,04	0,00	0,00	0,00
V	VYG 10	0,00	100,00	0,00	0,00	0,00
V	VYG 12	0,57	99,43	0,00	0,00	0,00
V	BLO 2	0,00	100,00	0,00	0,00	0,00
V	BLO 4	0,00	100,00	0,00	0,00	0,00
V	BLO 5	1,56	98,44	0,00	0,00	0,00
V	BLO 6	0,91	99,09	0,00	0,00	0,00
V	BOK 1	9,97	90,03	0,00	0,00	0,00
V	BOK 3	0,95	99,05	0,00	0,00	0,00
V	JAK 1	0,00	100,00	0,00	0,00	0,00
V	JAK 3	3,71	96,29	0,00	0,00	0,00
V	KAL 2	32,96	67,04	0,00	0,00	0,00
V	KAL 3	0,00	100,00	0,00	0,00	0,00
E	ELS 3	0,00	60,00	14,92	16,82	8,26
E	ELS 5	5,63	64,69	15,10	10,94	3,64
E	ELS 6	0,00	77,00	14,28	7,69	1,03
E	ELS 8	0,00	97,36	1,13	0,85	0,66
E	ELS 9	36,46	62,58	0,36	0,27	0,33
E	ELS 11	7,77	87,94	1,30	0,98	2,01
E	ELS 13	5,7	94,30	0,00	0,00	0,00
E	ELS 14	17,67	82,33	0,00	0,00	0,00
E	ELS 17	0,00	100,00	0,00	0,00	0,00
E	ELS 19	29,92	70,08	0,00	0,00	0,00
E	ELS 23	29,37	70,63	0,00	0,00	0,00
E	ELS 25	3,98	96,02	0,00	0,00	0,00
E	ELS 28	9,60	90,40	0,00	0,00	0,00
E	ELS 29	0,00	100,00	0,00	0,00	0,00

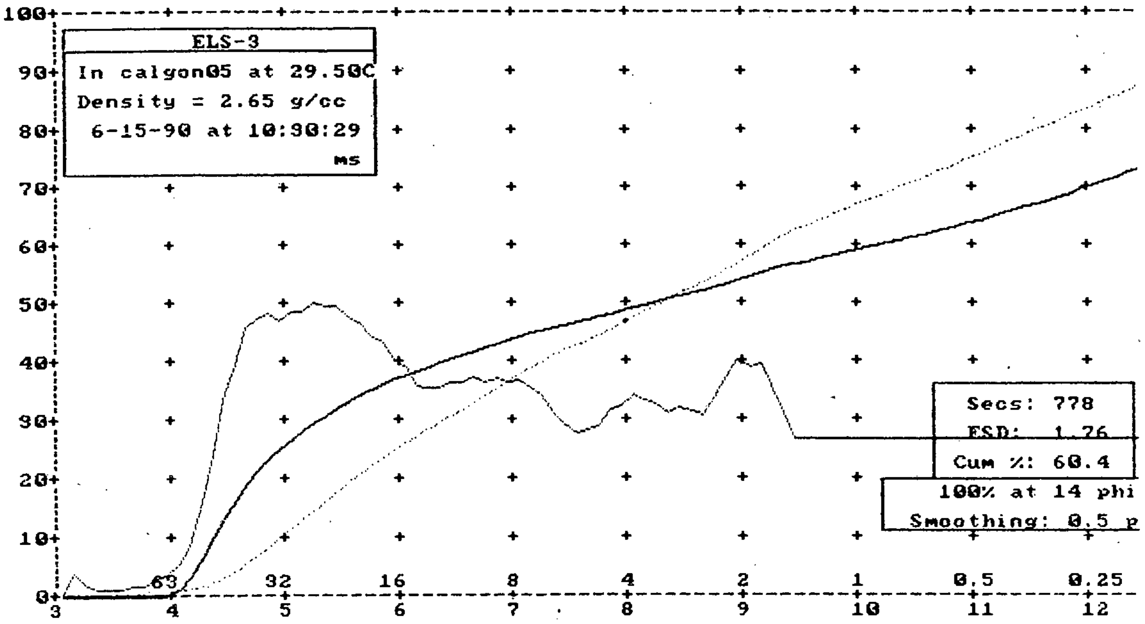
APPENDIX 3: RESULTS OF PRELIMINARY PARTICLE SIZE ANALYSIS OF ALL SEDIMENT SAMPLES

Group	Sample	% Gravel	% Sand	% Silt	% Clay	% Organics
				(determined on sedigraph)		
U	VYG 13a	6,04	93,96	0,00	0,00	0,00
U	VYG 13b	0,00	100,00	0,00	0,00	0,00
U	VYG 14a	0,74	99,26	0,00	0,00	0,00
U	VYG 14b	0,00	100,00	0,00	0,00	0,00
U	VYG 14c	0,00	100,00	0,00	0,00	0,00
U	VYG 15a	2,47	97,53	0,00	0,00	0,00
U	VYG 15b	1,78	98,22	0,00	0,00	0,00
U	VYG 15c	0,00	100,00	0,00	0,00	0,00
M	VYG 16a	0,00	100,00	0,00	0,00	0,00
M	VYG 16b	5,60	94,40	0,00	0,00	0,00
M	VYG 16c	0,00	100,00	0,00	0,00	0,00
M	VYG 17a	0,00	100,00	0,00	0,00	0,00
M	VYG 17b	0,47	99,53	0,00	0,00	0,00
M	VYG 17c	0,00	100,00	0,00	0,00	0,00
M	VYG 17d	0,00	100,00	0,00	0,00	0,00
L	BLA 10a	2,26	97,74	0,00	0,00	0,00
L	BLA 10b	0,00	100,00	0,00	0,00	0,00
L	BLA 10c	0,00	100,00	0,00	0,00	0,00
L	BLA 11a	0,27	99,73	0,00	0,00	0,00
L	BLA 11b	0,00	100,00	0,00	0,00	0,00
L	BLA 11c	0,00	100,00	0,00	0,00	0,00
X	BLA 12a	61,21	26,79	3,84	7,45	0,71
X	BLA 12b	66,06	31,15	0,91	1,64	0,24
X	BLA 12c	0,00	97,60	0,95	0,84	0,61
X	BLA 13a	0,00	58,45	8,36	5,35	27,84
X	BLA 13b	0,00	46,50	19,23	12,29	21,98
X	BLA 14a	10,54	78,72	5,16	3,59	1,99
X	BLA 14b	52,90	44,65	1,09	0,96	0,40
X	BLA 14c	0,00	96,25	1,27	1,13	1,35
X	BLA 15a	21,69	62,14	6,01	6,01	4,15
X	BLA 15b	9,75	76,44	7,41	3,81	2,59
X	BLA 16a	0,00	52,25	10,30	7,77	29,68
X	BLA 16b	0,00	59,60	9,72	7,34	23,34

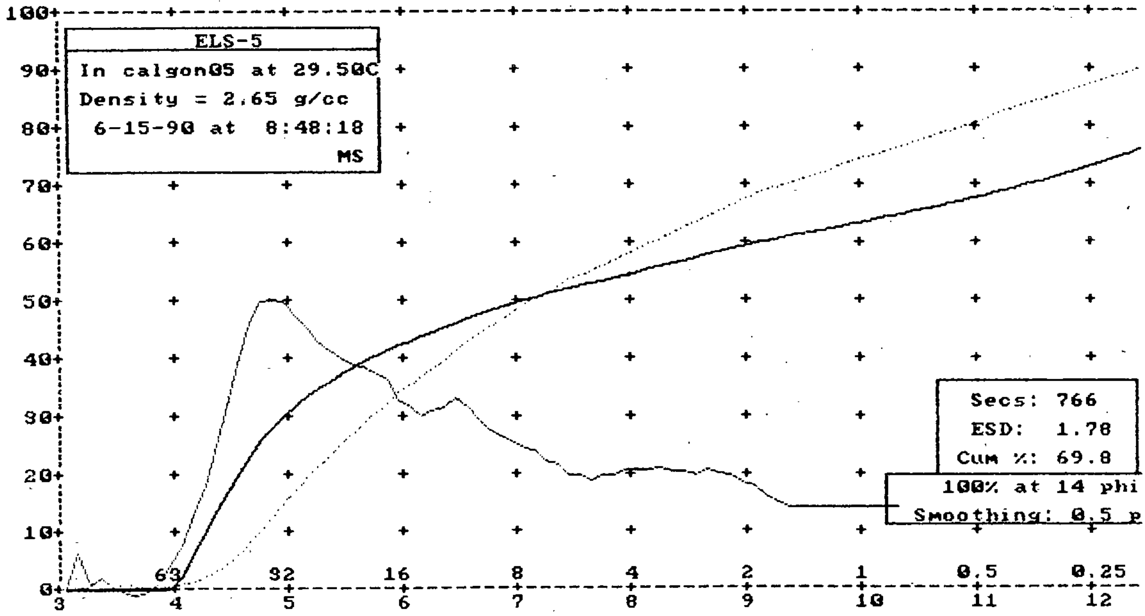
APPENDIX 4: RESULTS OF PARTICLE SIZE ANALYSIS OF FINE FRACTIONS OF SOME SAMPLES

Group	Sample	Mode (ϕ)	Median (ϕ)	Mean (ϕ)	Sorting (ϕ)	Skewness	Kurtosis
E	ELS 3	5,30	8,33	8,59	3,01	+0,14	0,72
E	ELS 5	4,85	7,15	7,90	2,95	+0,37	0,76
E	ELS 6	5,30	6,86	7,61	2,68	+0,43	1,00
X	BLA 12a	8,15	8,85	9,19	2,56	+0,17	0,88
X	BLA 12b	8,40	8,84	9,21	2,70	+0,16	0,80
X	BLA 13a	5,05	6,92	7,72	2,82	+0,42	0,85
X	BLA 13b	5,50	7,07	7,84	2,72	+0,42	0,90
X	BLA 14a	5,00	7,28	7,92	2,84	+0,34	0,85
X	BLA 15a	6,40	7,98	8,50	2,84	+0,26	0,77
X	BLA 15b	5,00	6,25	7,30	2,83	+0,54	0,87
X	BLA 16a	5,05	7,26	7,97	2,91	+0,35	0,78
X	BLA 16b	5,00	7,33	7,97	2,87	+0,33	0,82

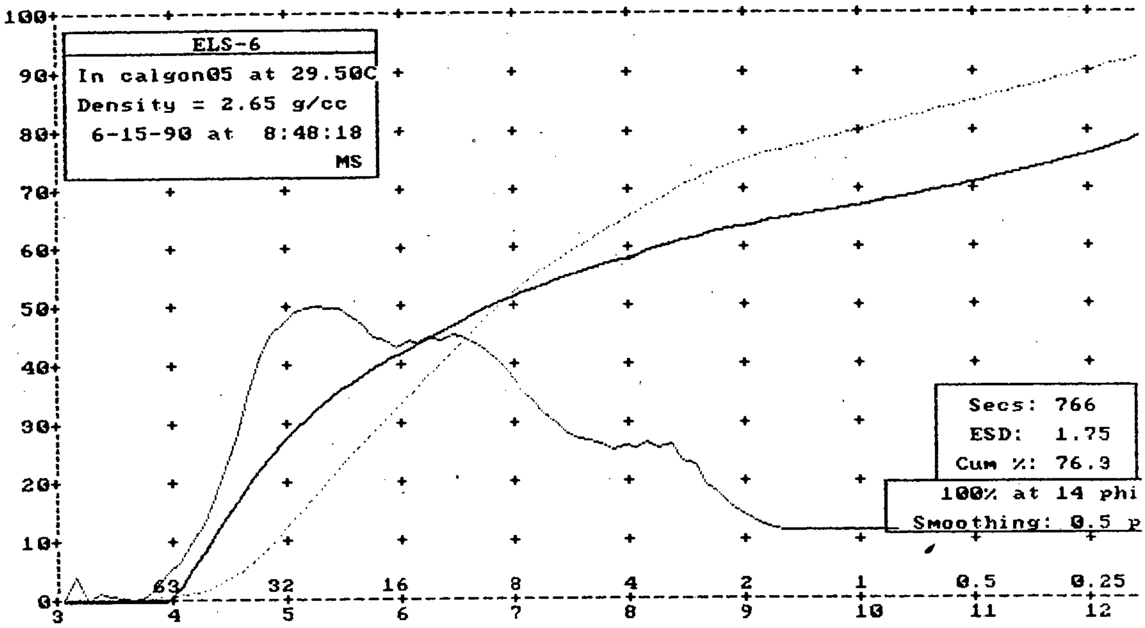
APPENDIX 5 : PARTICLE SIZE ANALYSIS PLOTS OF SOME SELECTED REPRESENTATIVE FINE FRACTIONS OF SAMPLES



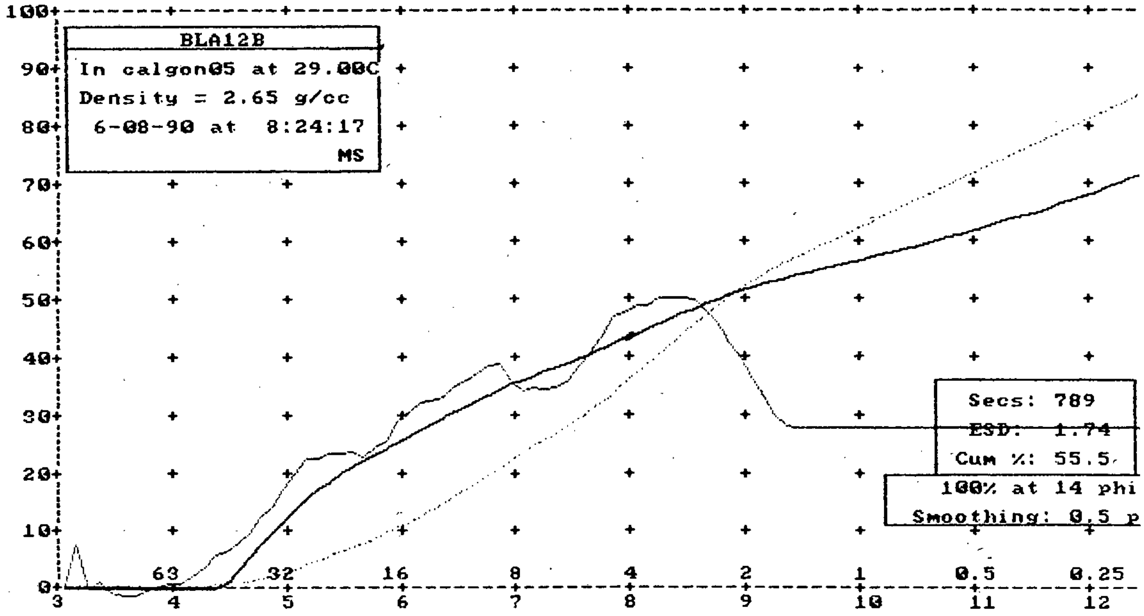
Graphical values (F&W):
Mean = 8.59 phi = 2.60u
Median = 8.33 phi = 3.11u
Sorting = 3.01 phi Skewness = 0.14 Kurtosis = 0.72



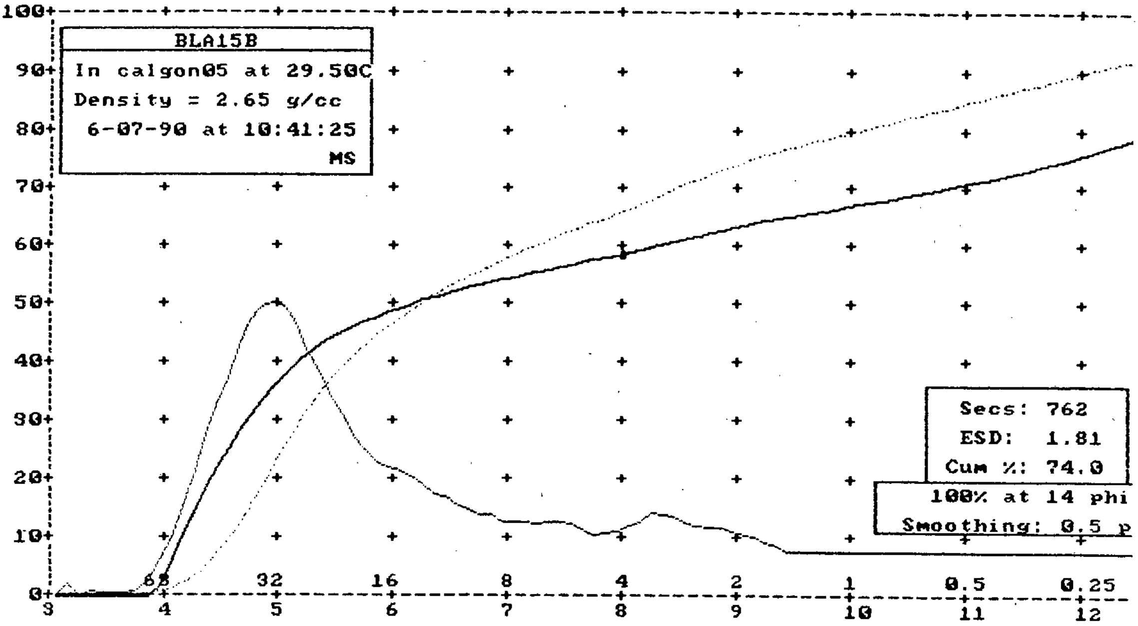
Graphical values (F&W):
Mean = 7.90 phi = 4.20u
Median = 7.15 phi = 7.02u
Sorting = 2.95 phi Skewness = 0.37 Kurtosis = 0.76



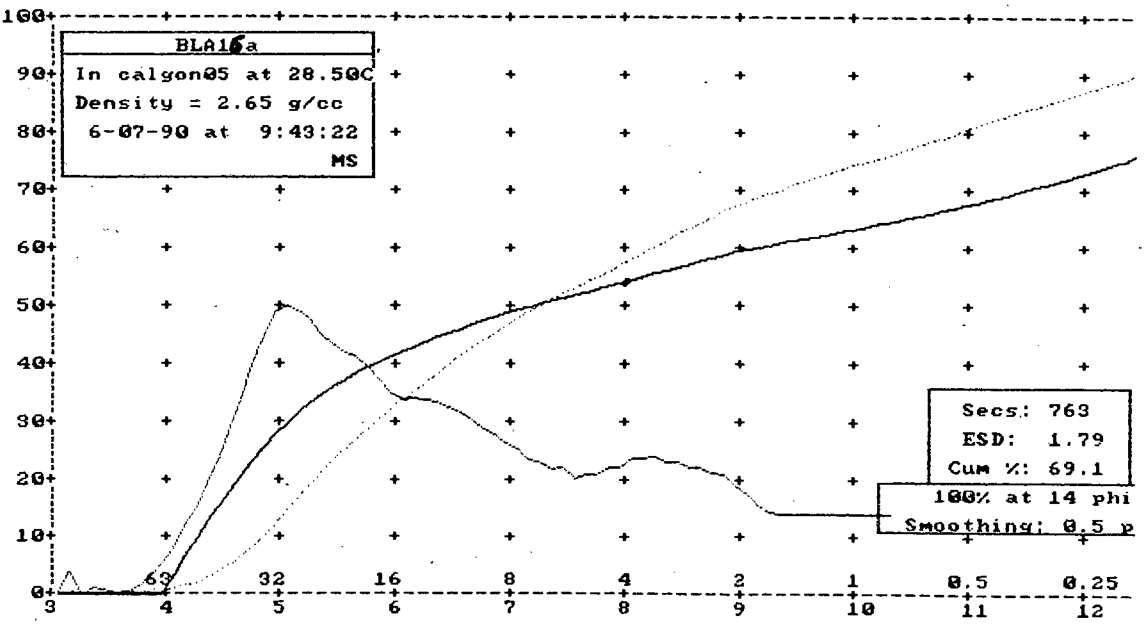
```
Graphical values (F&W):
  Mean =  7.61 phi =  5.11u
  Median =  6.86 phi =  8.58u
  Sorting = 2.68 phi    Skewness =  0.43    Kurtosis =  1.00
```



```
Graphical values (F&W):
  Mean =  9.21 phi =  1.69u
  Median =  8.84 phi =  2.18u
  Sorting = 2.70 phi    Skewness =  0.16    Kurtosis =  0.80
```



Graphical values (F&W):
Mean = 7.30 phi = 6.37u
Median = 6.25 phi = 13.12u
Sorting = 2.83 phi Skewness = 0.54 Kurtosis = 0.87



Graphical values (F&W):
Mean = 7.97 phi = 3.99u
Median = 7.26 phi = 6.51u
Sorting = 2.91 phi Skewness = 0.35 Kurtosis = 0.78

APPENDIX 6: DETAILS OF THE SETTLING TUBE PARTICLE SIZE ANALYSER

Fall height:	1,42 m.
Diameter:	18 cm.
Settling liquid:	Water at 19°C to 21°C.
Assumed density of settling sediment grains:	2,65 g/cm^3 (quartz).
Assumed shape of settling sediment grains:	Spherical.
Initial sample holder at top of tube:	62,5 micron gauze.
Mounting liquid:	50 % Extran solution.
Sample collector at base of tube:	Perspex pan suspended by copper wires.
Mass balance:	Electronic Mettler PL200.
Calculator:	Desk-top Hewlett Packard 9830A.
Program:	HP-BASIC.
Reading intervals (time):	1,5 seconds.
Reading intervals (mass):	0,1 ϕ interval.

Formula relating grain settling time (and therefore grain settling velocity) to grain size/diameter (Brink and Rogers, 1985):

$$\frac{D = \mathrm{Log}\ 10\ [(37{,}4dmV^2) + \sqrt{((0{,}136dwV^2) - 2942(dm - dw)\ (-6vwV - 0{,}011 - dwV^2))}}{\sqrt{2697(dm - dw)}}$$

where: D = grain size/diameter

V = settling velocity = $\frac{\text{fall height}}{\text{settling time}}$

vw = water viscosity) dependent upon water temperature
dw = water density)

dm = mineral density = 2,65 g/cm^3 = specific gravity of quartz

(This formula is derived from the application of the Stokes Settling Law to the settling tube).

The graphical statistical parameters of the grain size distribution have been calculated using the formulae devised by Folk and Ward (1957). These are:

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

median size $= \phi 50$

Sorting $= \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6{,}6}$

Skewness $= \frac{\phi 16 + \phi 84 - 2\phi 50}{2(\phi 84 - \phi 16)} + \frac{\phi 5 + \phi 95 - 2\phi 50}{2(\phi 95 - \phi 5)}$

Kurtosis $= \frac{\phi 95 - \phi 5}{2{,}44(\phi 75 - \phi 25)}$

where: ϕX = phi value at cumulative mass % X on cumulative frequency curve of particle size distribution.

Note: Values for mean, median, mode and sorting are measured in phi units; values for skewness and kurtosis are dimensionless numbers. The phi value of the mode size occurs at the steepest point of the cumulative frequency curve, or at the highest point of the frequency curve.

APPENDIX 7: RESULTS OF PARTICLE SIZE ANALYSIS OF SAND FRACTIONS OF ALL SAMPLES

Group	Sample	Mode	Median	Mean	Sorting	Skewness	Kurtosis
B	BLA 1	0,20	0,18	0,17	0,31	-0,01	1,02
B	BLA 3	1,40	1,29	1,25	0,47	-0,15	1,08
B	BLA 5	1,00	0,95	0,94	0,38	-0,02	1,03
B	BLA 7	0,60	0,57	0,56	0,57	+0,04	1,03
B	BLA 9	1,30	0,91	0,87	0,69	-0,08	0,91
B	KRO 1	0,35	0,73	0,76	0,66	+0,07	0,81
B	KRO 4	1,70	1,53	1,47	0,54	-0,17	1,04
B	KRO 6	1,45	1,31	1,25	0,46	-0,22	1,02
V	VYG 1	1,55	1,52	1,51	0,38	-0,03	1,04
V	VYG 3	1,30	1,25	1,23	0,43	-0,09	1,03
V	VYG 5	1,15	1,11	1,12	0,49	+0,02	0,98
V	VYG 7	0,95	0,87	0,86	0,40	-0,04	1,00
V	VYG 9	1,00	0,93	0,92	0,42	-0,02	0,99
V	VYG 10	0,75	0,71	0,72	0,44	+0,04	0,99
V	VYG 12	0,85	0,84	0,84	0,46	0,00	1,01
V	BLO 2	1,00	0,80	0,77	0,41	-0,09	0,89
V	BLO 4	1,00	0,96	0,94	0,41	-0,08	1,04
V	BLO 5	0,95	0,92	0,92	0,43	+0,01	1,06
V	BLO 6	0,85	0,80	0,79	0,43	-0,01	1,00
V	BOK 1	1,55	1,45	1,41	0,44	-0,19	1,14
V	BOK 3	1,75	1,66	1,62	0,41	-0,22	1,28
V	JAK 1	1,00	1,01	1,00	0,44	-0,02	1,07
V	JAK 3	0,75	0,70	0,70	0,42	+0,02	1,01
V	KAL 2	1,15	1,05	1,03	0,43	-0,09	1,11
V	KAL 3	1,45	1,39	1,38	0,52	-0,01	1,01
E	ELS 3	2,30	1,92	1,83	0,95	-0,09	0,95
E	ELS 5	2,60	2,46	2,39	0,78	-0,17	1,16
E	ELS 6	2,45	2,27	2,18	0,72	-0,22	1,10
E	ELS 8	2,35	2,19	2,11	0,60	-0,22	1,16
E	ELS 9	1,35	1,22	1,17	0,63	-0,11	1,11
E	ELS 11	1,95	1,85	1,81	0,57	-0,14	1,17
E	ELS 13	2,35	2,32	2,30	0,43	-0,11	1,30
E	ELS 14	2,00	1,84	1,71	0,70	-0,27	1,08
E	ELS 17	2,00	1,95	1,90	0,49	-0,17	1,15
E	ELS 19	1,20	1,07	1,02	0,53	-0,16	1,06
E	ELS 23	0,75	0,65	0,63	0,42	-0,06	1,00
E	ELS 25	1,35	1,33	1,33	0,61	-0,01	1,05
E	ELS 28	1,25	1,24	1,23	0,37	-0,05	1,13
E	ELS 29	1,70	1,56	1,50	0,49	-0,25	1,20
U	VYG 13a	1,30	1,10	1,09	0,60	-0,03	0,98
U	VYG 13b	1,35	1,26	1,22	0,45	-0,19	1,11
U	VYG 14a	1,30	1,21	1,18	0,44	0,14	1,08
U	VYG 14b	1,00	0,89	0,88	0,45	-0,03	0,93
U	VYG 14c	1,00	0,91	0,89	0,42	-0,04	0,97
U	VYG 15a	1,05	0,95	0,93	0,49	-0,05	0,93
U	VYG 15b	1,45	1,20	1,15	0,55	-0,12	0,91
U	VYG 15c	1,30	1,15	1,12	0,41	-0,14	1,07

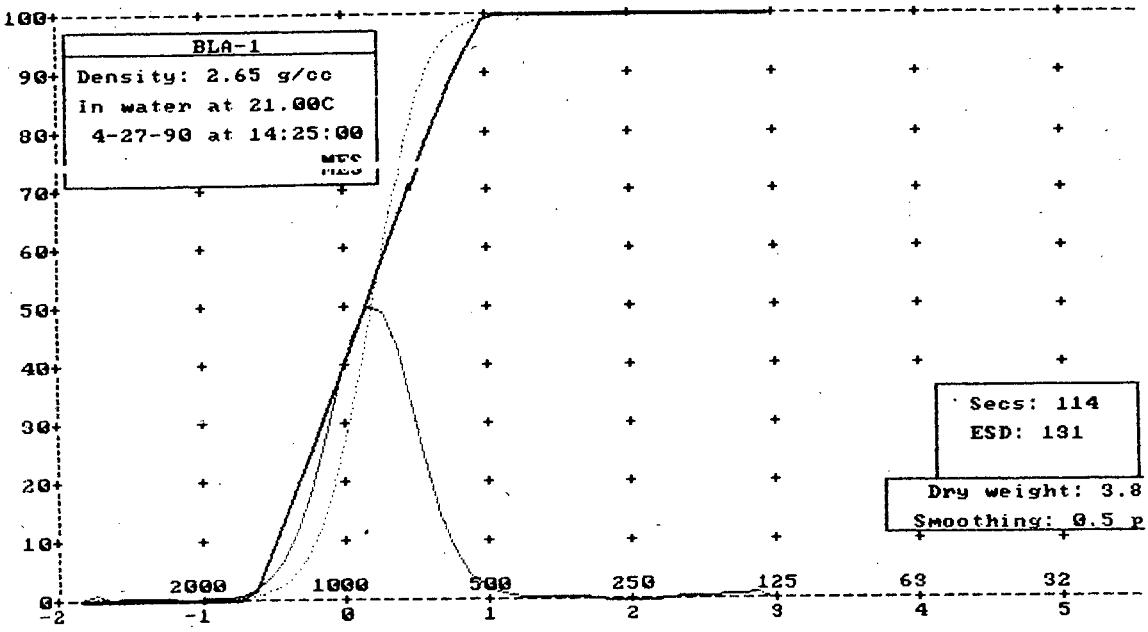
APPENDIX 7: RESULTS OF PARTICLE SIZE ANALYSIS OF SAND FRACTIONS OF ALL SAMPLES

Group	Sample	Mode	Median	Mean	Sorting	Skewness	Kurtosis
M	VYG 16a	1,30	1,25	1,23	0,41	-0,09	1,10
M	VYG 16b	1,15	1,02	1,02	0,56	+0,04	0,98
M	VYG 16c	1,65	1,57	1,54	0,54	-0,06	1,06
M	VYG 17a	1,45	1,29	1,23	0,50	-0,18	0,99
M	VYG 17b	1,70	1,56	1,51	0,55	-0,10	1,00
M	VYG 17c	1,70	1,38	1,33	0,62	-0,11	0,92
M	VYG 17d	2,35	2,32	2,32	0,31	+0,04	1,06
L	BLA 10a	1,15	1,09	1,07	0,46	-0,08	1,07
L	BLA 10b	1,20	1,23	1,24	0,51	+0,05	1,08
L	BLA 10c	2,35	2,39	2,40	0,31	+0,09	1,12
L	BLA 11a	1,15	1,01	0,97	0,49	-0,11	0,98
L	BLA 11b	2,00	1,97	1,95	0,40	-0,12	1,18
L	BLA 11c	2,40	2,41	2,41	0,31	-0,02	1,16
X	BLA 12a	2,15	1,97	1,78	0,96	-0,28	1,12
X	BLA 12b	1,80	1,13	1,16	0,86	+0,10	0,85
X	BLA 12c	2,55	2;50	2,36	0,64	-0,35	1,37
X	BLA 13a	2,75	2,77	2,78	0,41	+0,03	1,16
X	BLA 13b	2,85	2,90	2,93	0,40	+0,10	1,12
X	BLA 14a	2,20	2,02	1,94	0,69	-0,19	1,07
X	BLA 14b	2,25	2,07	1,80	1,07	-0,55	1,90
X	BLA 14c	2,60	2,64	2,65	0,36	+0,07	1,11
X	BLA 15a	2,15	2,05	1,97	0,90	-0,17	1,23
X	BLA 15b	2,95	2,88	2,73	0,81	-0,41	1,94
X	BLA 16a	3,00	2,99	2,99	0,54	-0,21	1,97
X	BLA 16b	2,05	1,86	1,82	0,98	-0,06	1,09

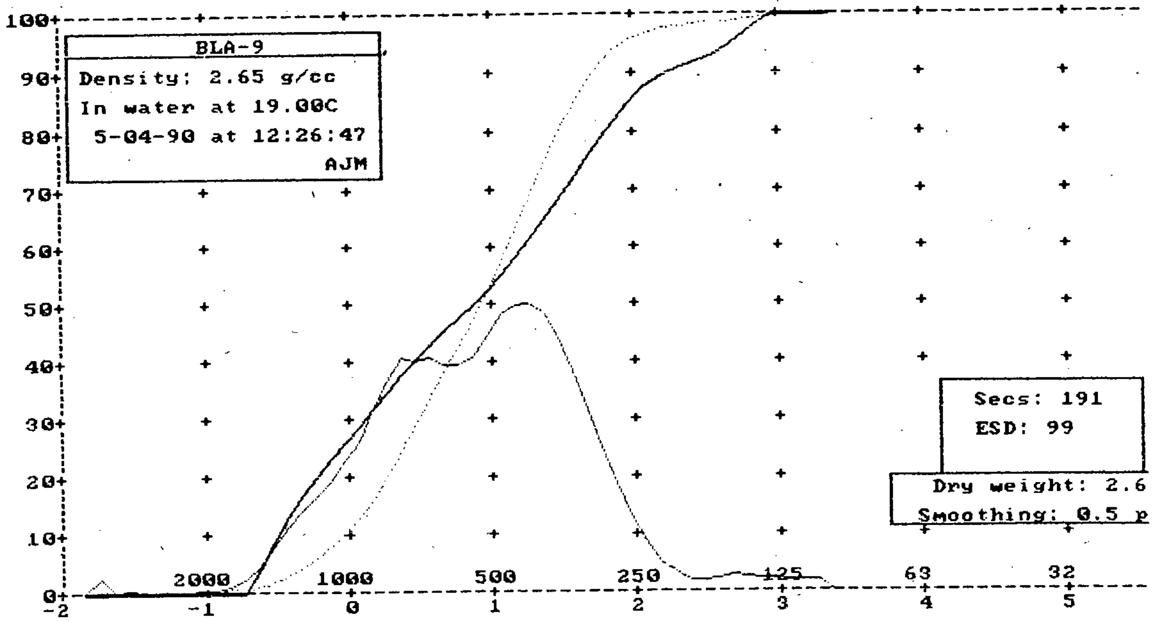
APPENDIX 8 : GROUP MEANS OF PARTICLE SIZE ANALYSIS RESULTS PARAMETERS/VARIABLES

Size class %/ parameter value		Data set mean %/ value	Groups in data set						
			B	V	E	U	M	L	X
in entire sample	Gravel %	8,4	19,9	3,1	10,5	1,4	0,9	0,9	18,7
	Sand %	88,2	80,1	96,9	83,2	98,6	99,1	99,6	67,9
	Silt %	1,9	0,0	0,0	3,5	0,0	0,0	0,0	7,6
	Clay %	1,5	0,0	0,0	2,8	0,0	0,0	0,0	5,8
in sand fraction	Mode (ϕ)	1,57	1,00	1,12	1,83	1,22	1,61	1,71	2,44
	Median (ϕ)	1,47	0,93	1,06	1,70	1,08	1,48	1,68	2,31
	Mean (ϕ)	1,44	0,91	1,04	1,65	1,06	1,45	1,67	2,24
	Sorting (ϕ)	0,53	0,51	0,43	0,59	0,48	0,50	0,41	0,72
	Skewness	-0,09	-0,06	-0,05	-0,14	-0,09	-0,06	-0,03	-0,16
	Kurtosis	1,09	0,99	1,04	1,11	1,00	1,01	1,10	1,33

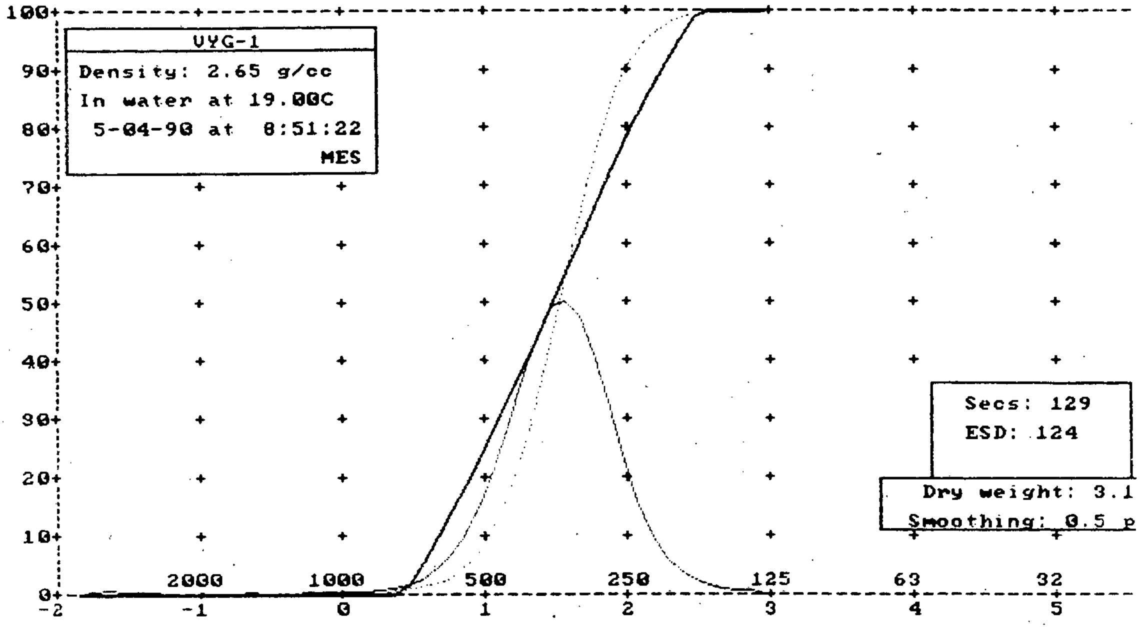
APPENDIX 9: PARTICLE SIZE ANALYSIS PLOTS OF SOME SELECTED REPRESENTATIVE SAND FRACTIONS OF SAMPLES



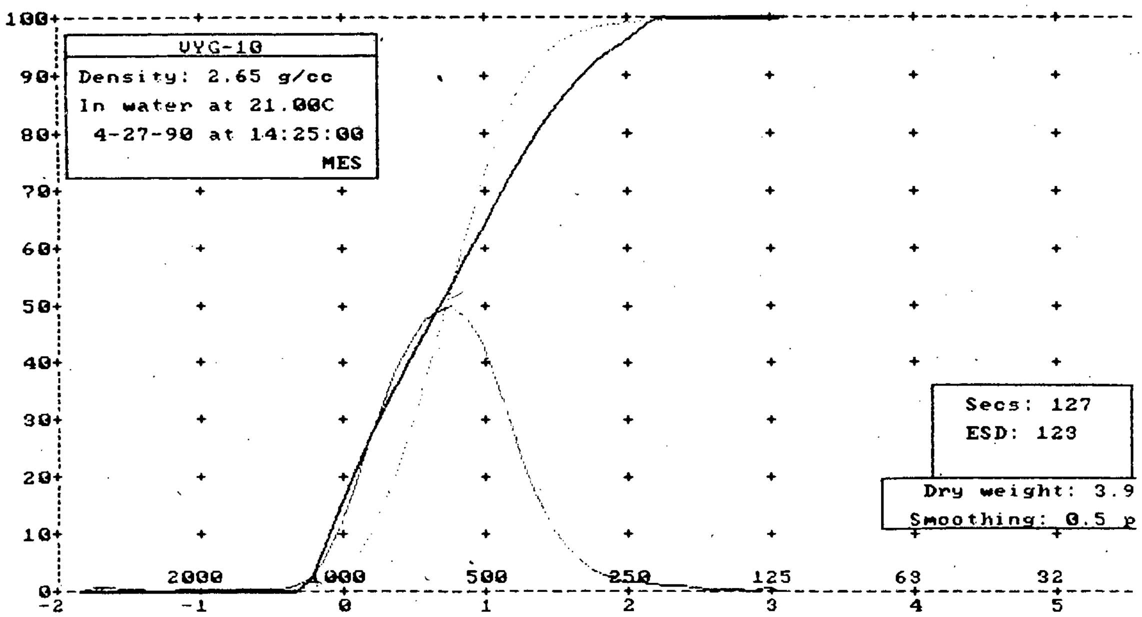
Graphical values (F&W):
Mean = 0.17 phi = 885.82u
Median (phi50) = 0.18 phi = 884.77u
Sorting = 0.31 phi Skewness = -0.01 Kurtosis = 1.02



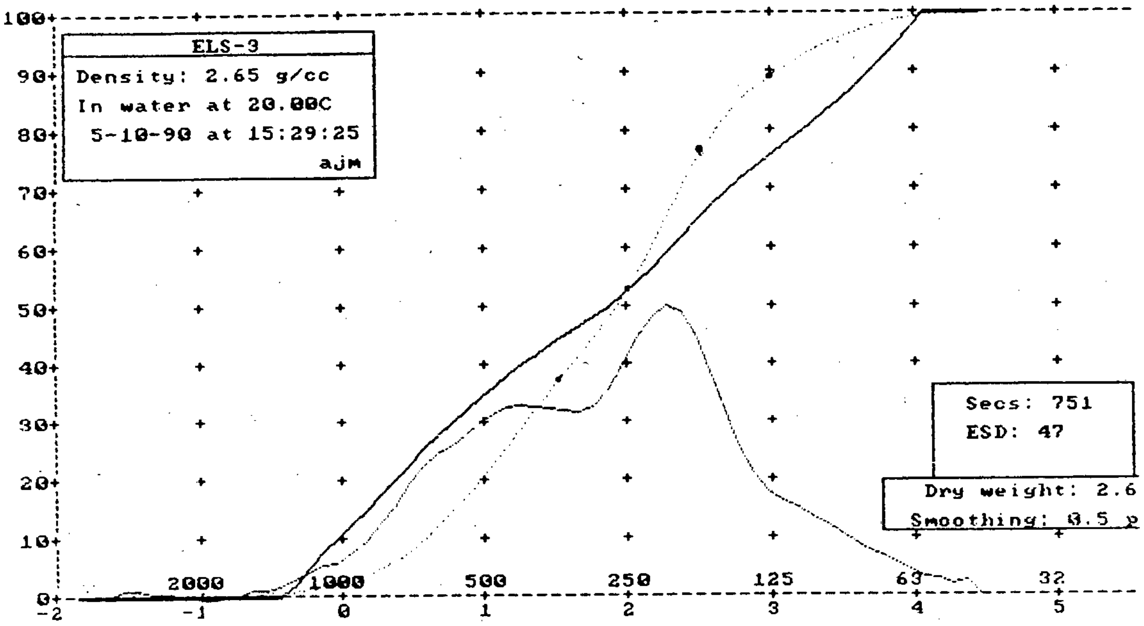
Graphical values (F&W):
Mean = 0.87 phi = 546.13u
Median (phi50) = 0.91 phi = 530.55u
Sorting = 0.69 phi Skewness = -0.08 Kurtosis = 0.91



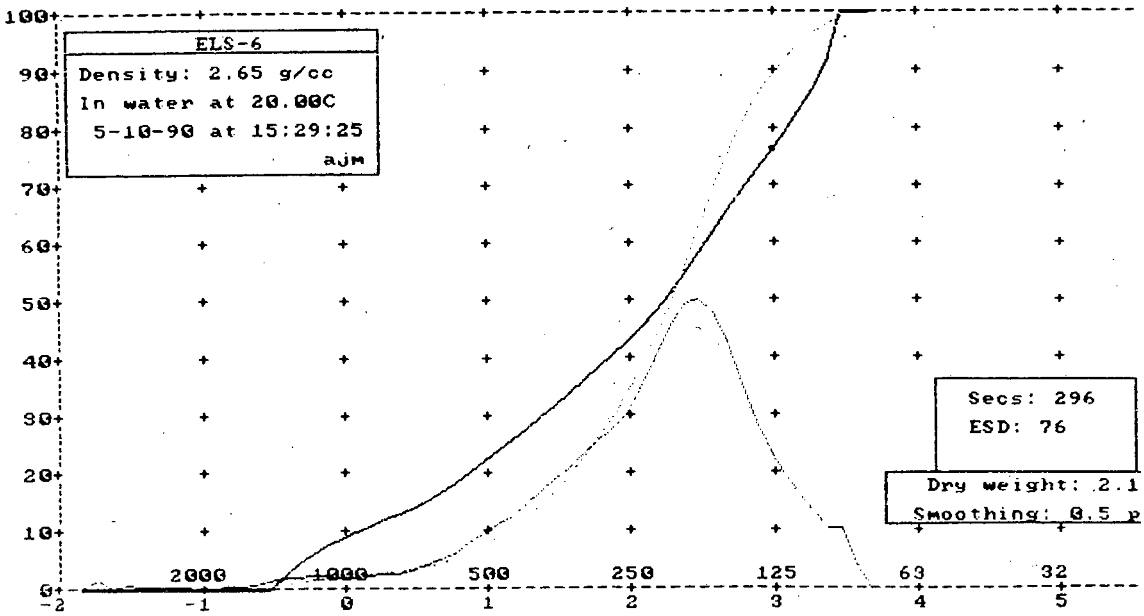
```
Graphical values (F&W):
  Mean =  1.51 phi = 351.50u
  Median ( phi50 ) =  1.52 phi = 349.86u
  Sorting = 0.38 phi    Skewness = -0.03    Kurtosis =  1.04
```



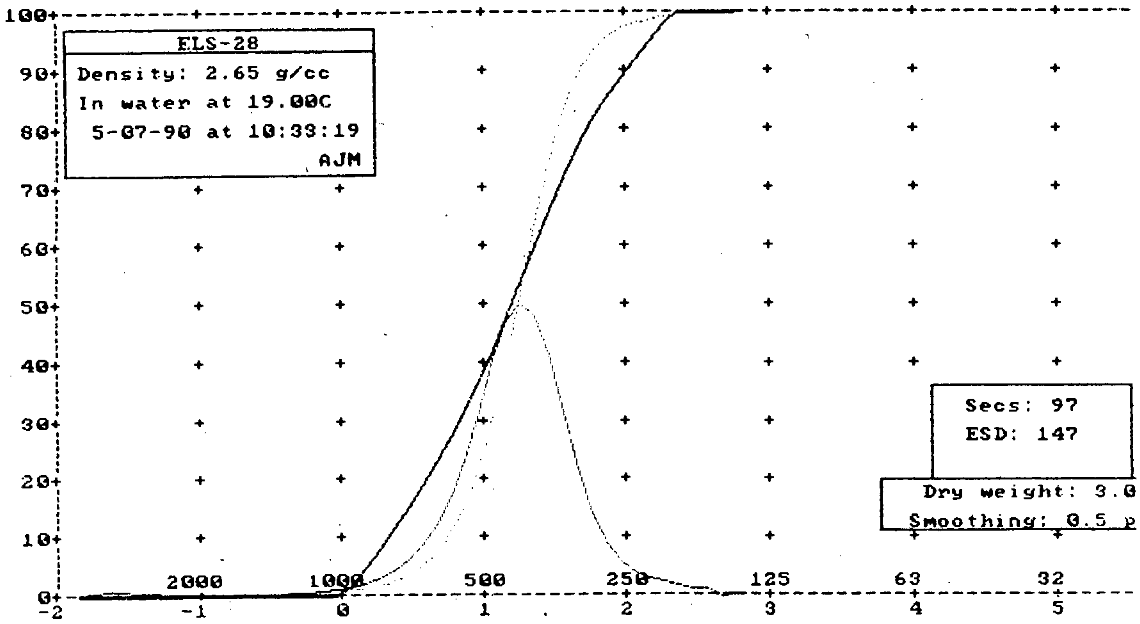
```
Graphical values (F&W):
  Mean =  0.72 phi = 608.12u
  Median ( phi50) =  0.71 phi = 610.06u
  Sorting = 0.44 phi    Skewness = 0.04    Kurtosis =  0.99
```



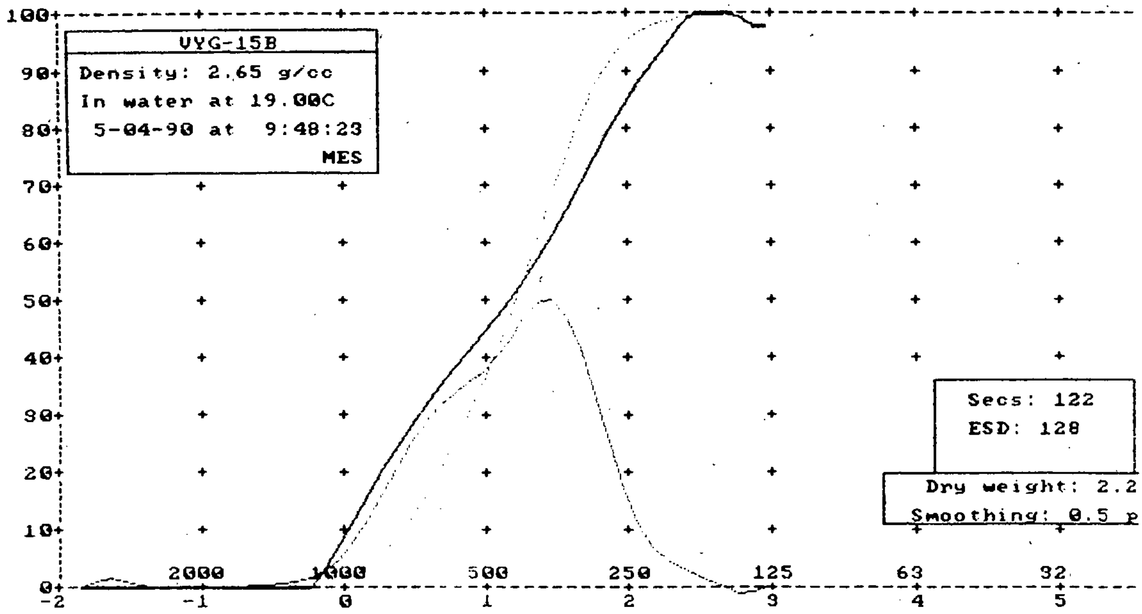
```
Graphical values (F&W):
  Mean =  1.83 phi = 281.90u
  Median ( phi50) =  1.92 phi = 264.84u
  Sorting = 0.95 phi    Skewness = -0.09    Kurtosis =  0.35
```



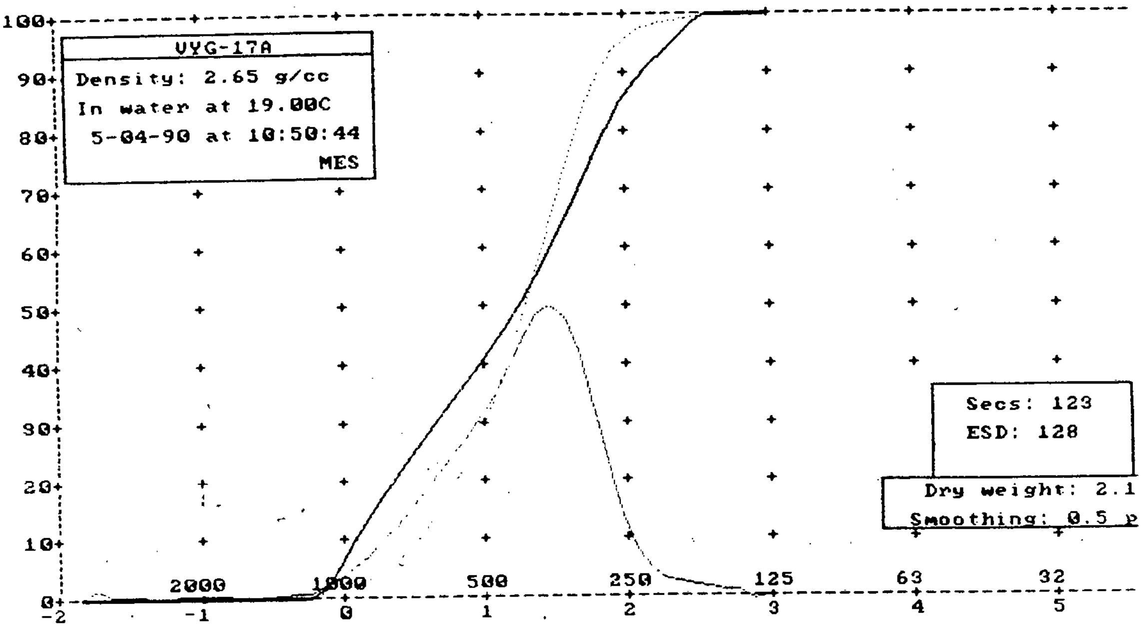
```
Graphical values (F&W):
  Mean =  2.18 phi = 220.93u
  Median ( phi50) =  2.27 phi = 206.94u
  Sorting = 0.72 phi    Skewness = -0.22    Kurtosis =  1.10
```



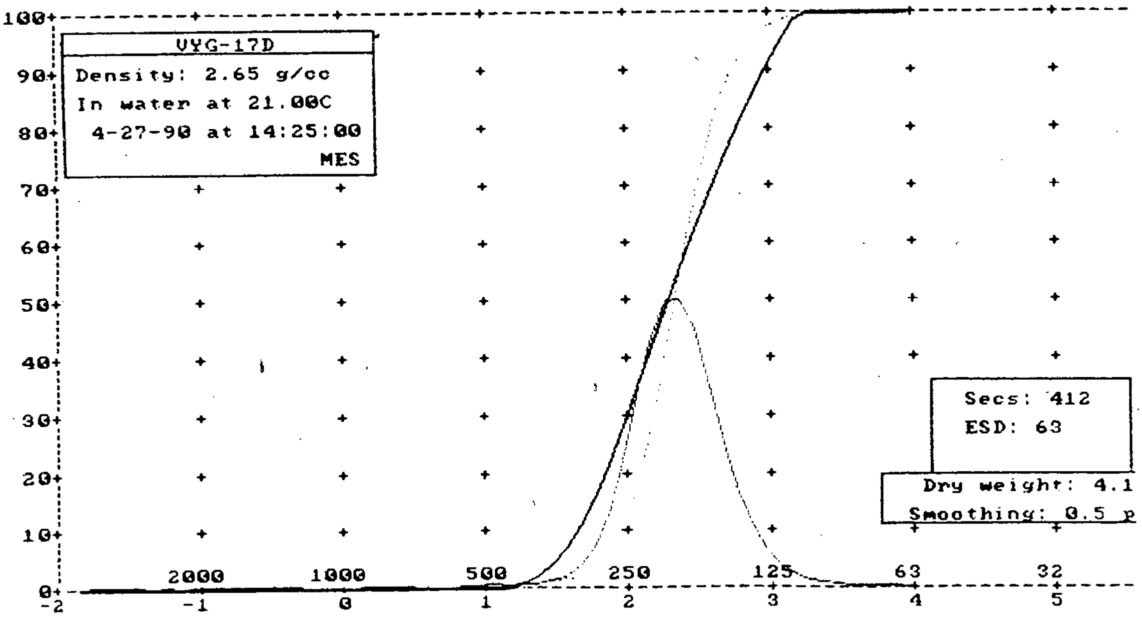
```
Graphical values (F&w :
  Mean =  1.23 phi = 427.78u
  Median ( phi50) =  1.24 phi = 424.70u
  Sorting = 0.37 phi    Skewness = -0.05    Kurtosis =  1.13
```



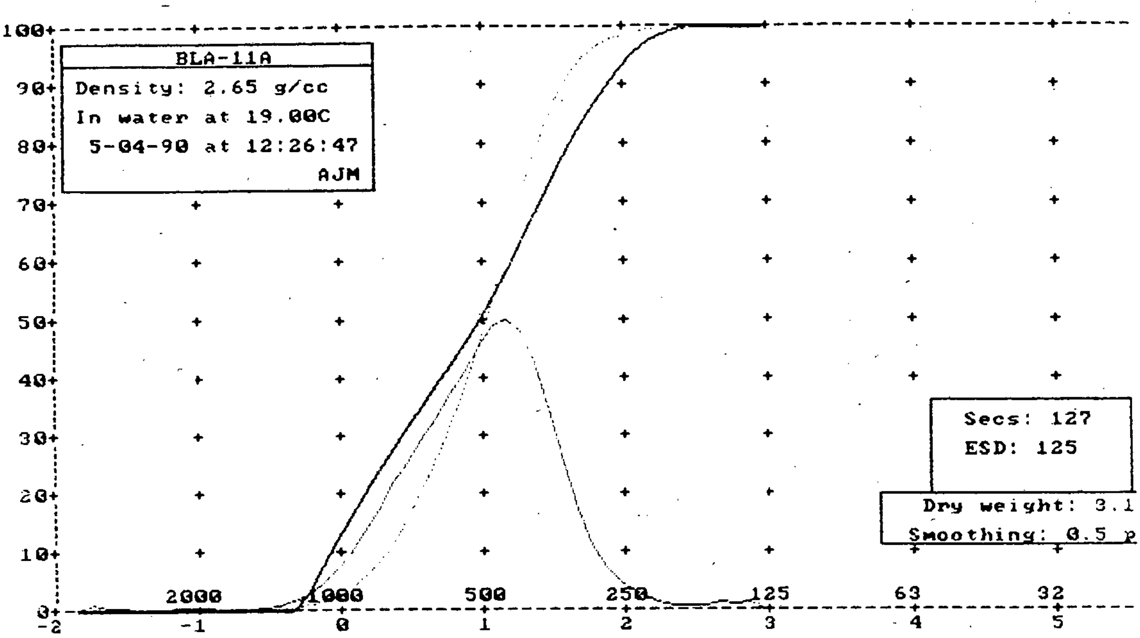
```
Graphical values (F&w):
  Mean =  1.15 phi = 450.02u
  Median ( phi50) =  1.20 phi = 434.84u
  Sorting = 0.55 phi    Skewness = -0.12    Kurtosis =  0.91
```



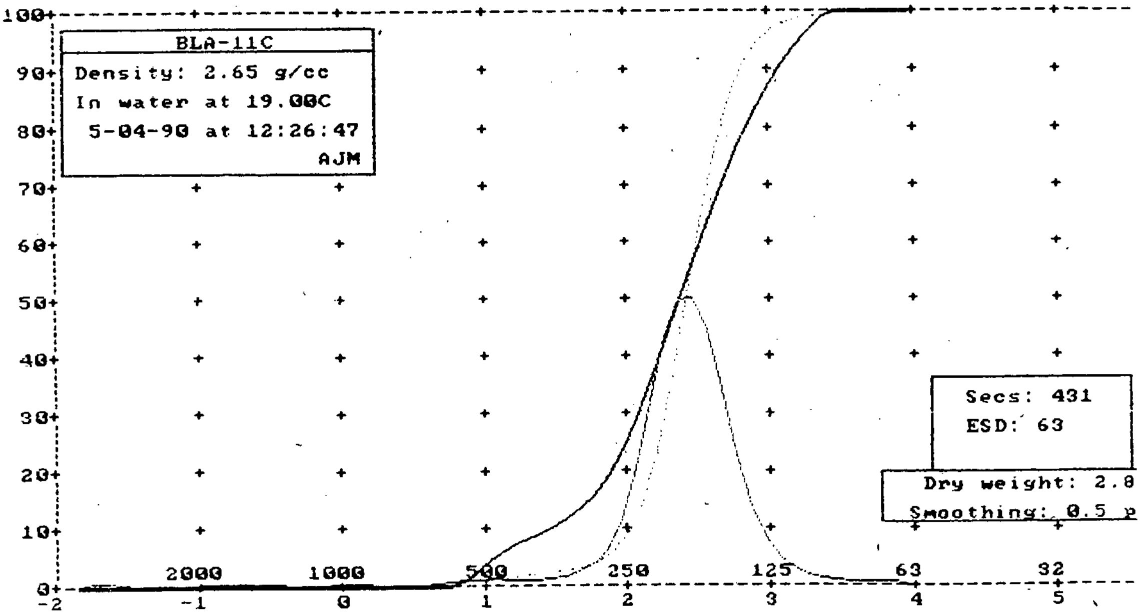
```
Graphical values (FSW):
  Mean =  1.23 phi = 427.04u
  Median ( phi50) =  1.29 phi = 409.71u
  Sorting = 0.50 phi     Skewness = -0.18    Kurtosis =  0.99
```



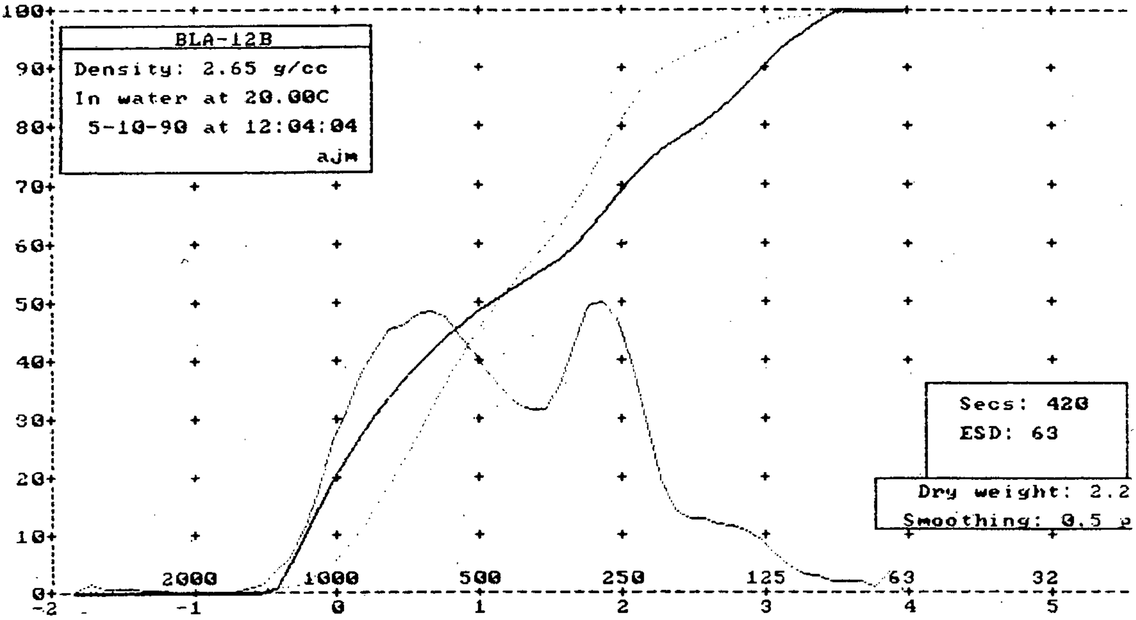
```
Graphical values (FSW):
  Mean =  2.32 phi = 199.61u
  Median ( phi50) =  2.32 phi = 200.37u
  Sorting = 0.31 phi     Skewness =  0.04    Kurtosis =  1.05
```



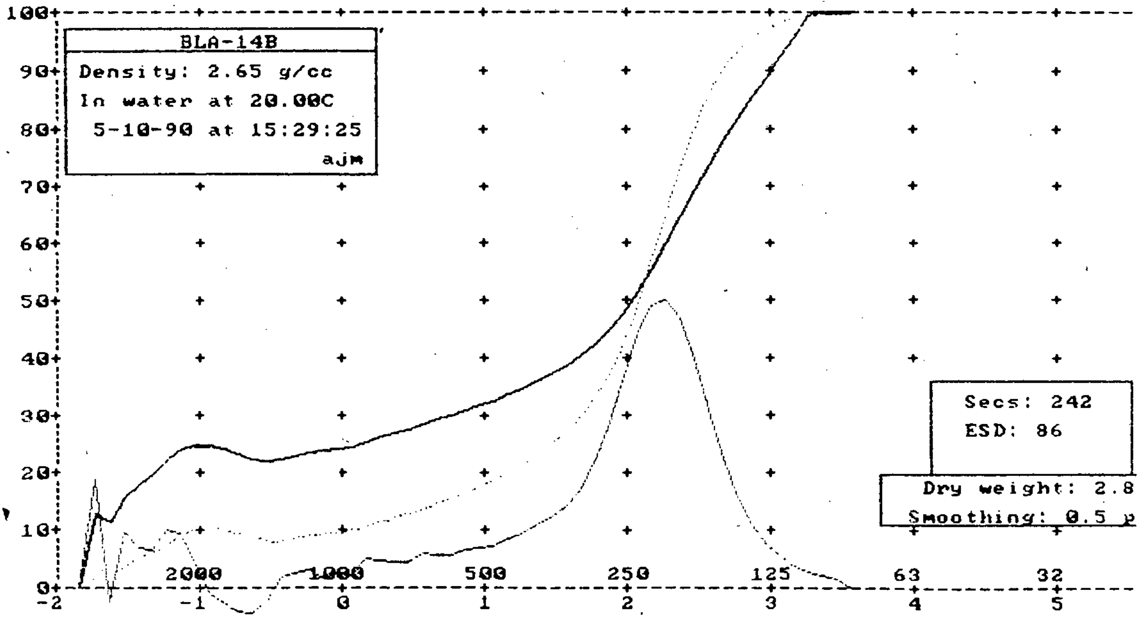
Graphical values (F&W):
Mean = 0.97 phi = 510.59u
Median (phi50) = 1.01 phi = 496.35u
Sorting = 0.48 phi Skewness = -0.11 Kurtosis = 0.98



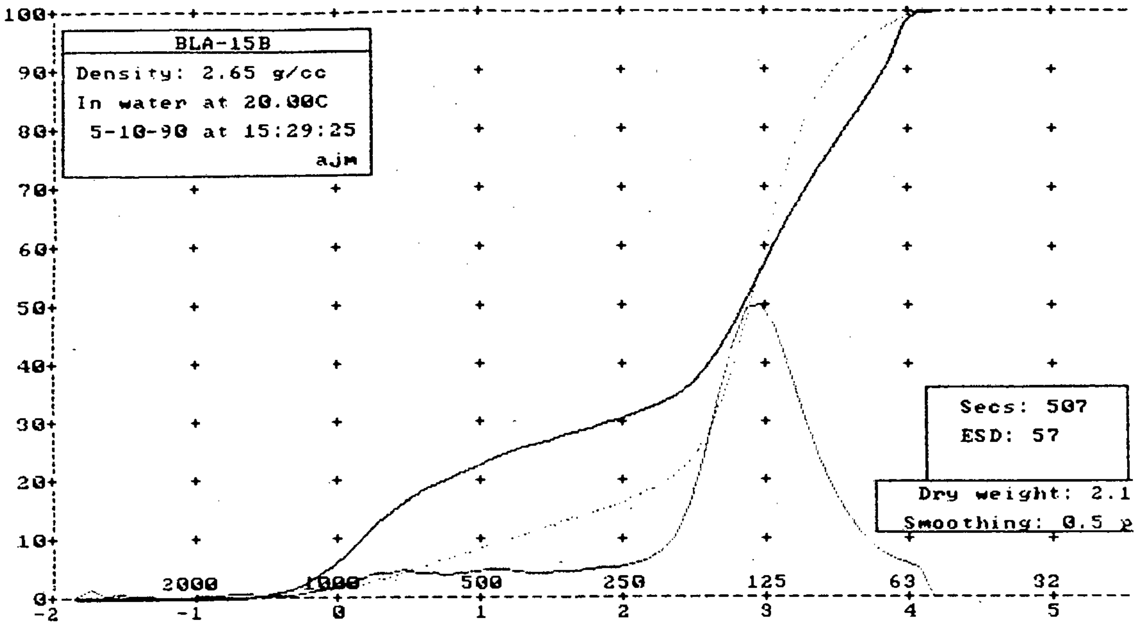
Graphical values (F&W):
Mean = 2.41 phi = 188.49u
Median (phi50) = 2.41 phi = 188.41u
Sorting = 0.31 phi Skewness = -0.02 Kurtosis = 1.16



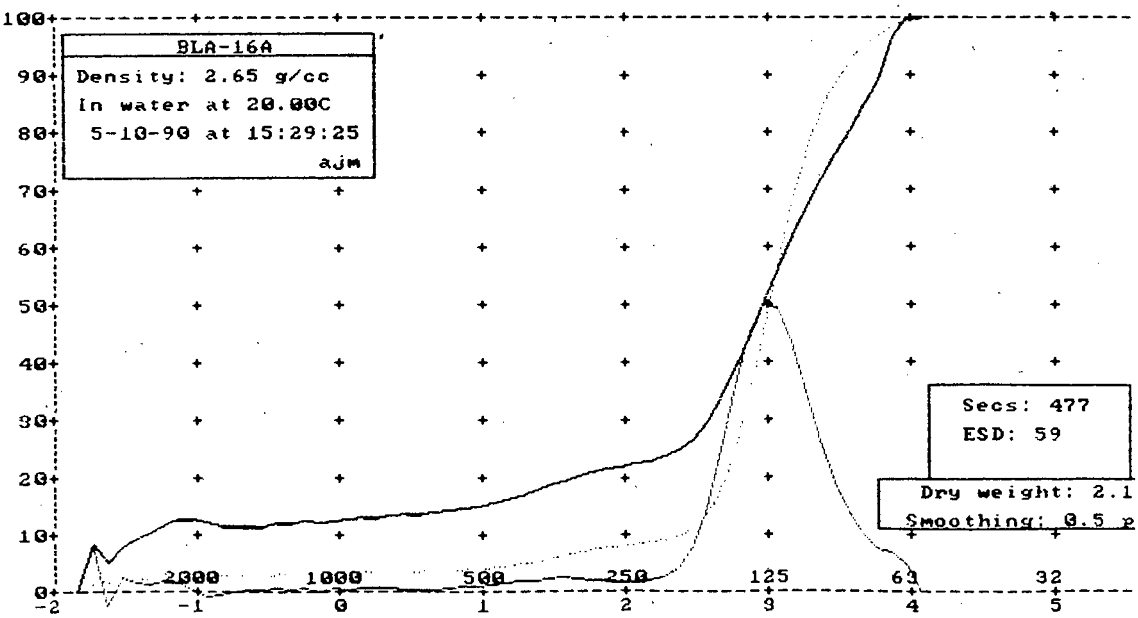
```
. Graphical values (F&W):
    Mean =  1.16 phi = 447.70u
    Median ( phi50) =  1.13 phi = 458.18u
    Sorting = 0.86 phi     Skewness =  0.10    Kurtosis =  0.35
```



```
Graphical values (F&W):
  Mean =  1.80 phi = 286.22u
  Median ( phi50) =  2.07 phi = 238.24u
  Sorting = 1.07 phi     Skewness = -0.55    Kurtosis =  1.90
```



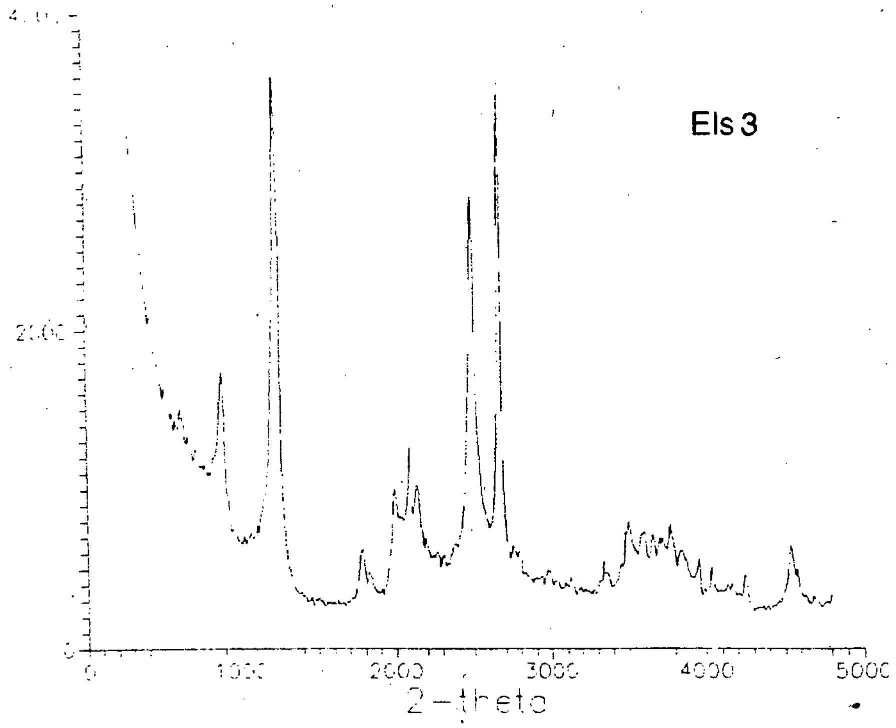
```
Graphical values (F&W):
  Mean =  2.73 phi = 151.12u
  Median ( phi50) =  2.88 phi = 136.22u
  Sorting = 0.81 phi     Skewness = -0.41     Kurtosis =  1.94
```

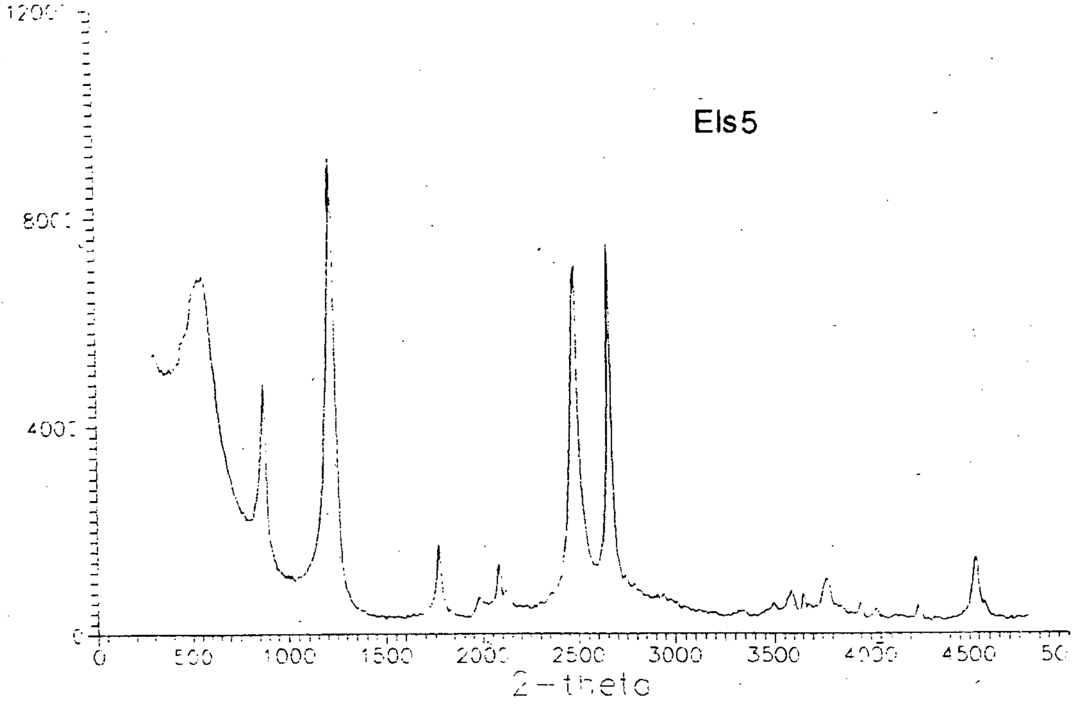


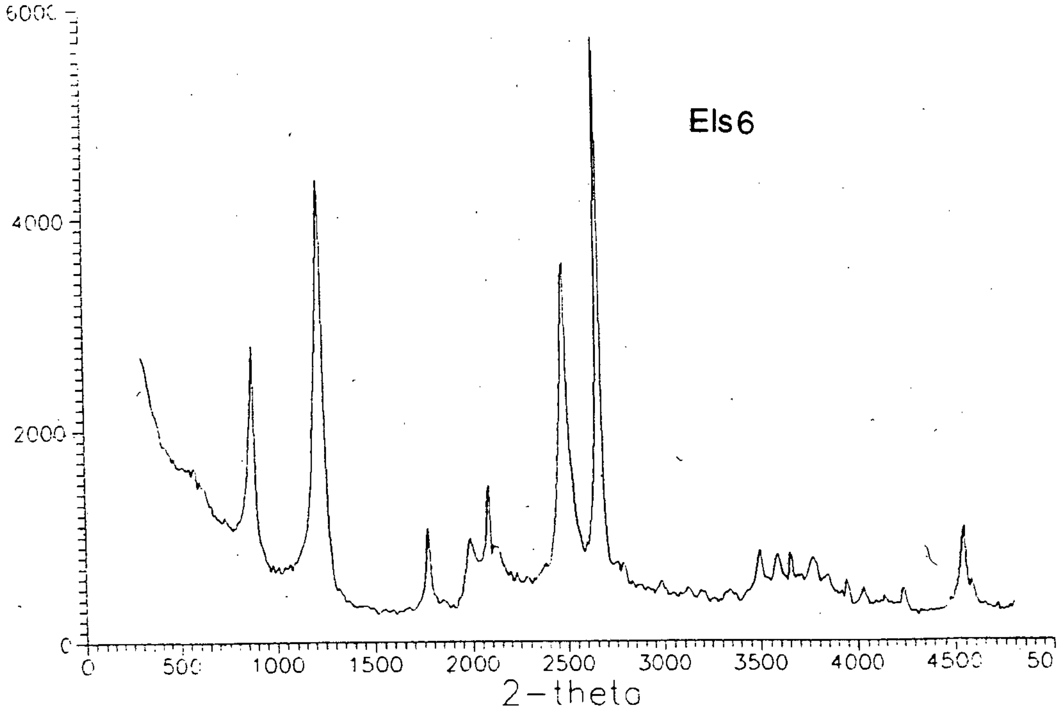
```
Graphical values (F&W):
  Mean =  2.99 phi = 125.79u
  Median ( phi50) =  2.99 phi = 125.83u
  Sorting = 0.54 phi     Skewness = -0.21     Kurtosis =  1.87
```

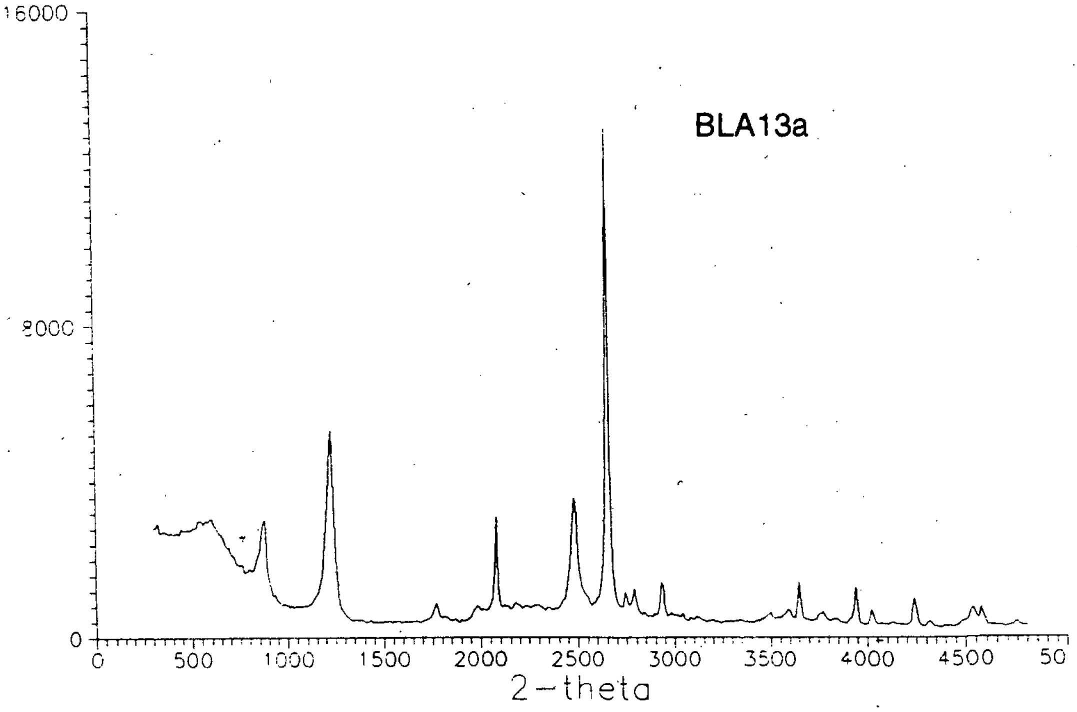
APPENDIX 10: DETAILS OF X-RAY DIFFRACTION EQUIPMENT	
Spectrometer:	Philips PW1130 X-ray.
Tube:	Cu KV.
Generator:	40kV, 30mA.
Radiation:	Cu K-alpha.
Filter:	None.
Slits:	½°, ½°, 1°.
Time constant:	2 seconds.
Scan angles:	3° to 48° 2-theta.
Scan speed:	1° per minute.
Count period:	4 seconds.
Sample:	Non-randomly oriented on a glass slide.

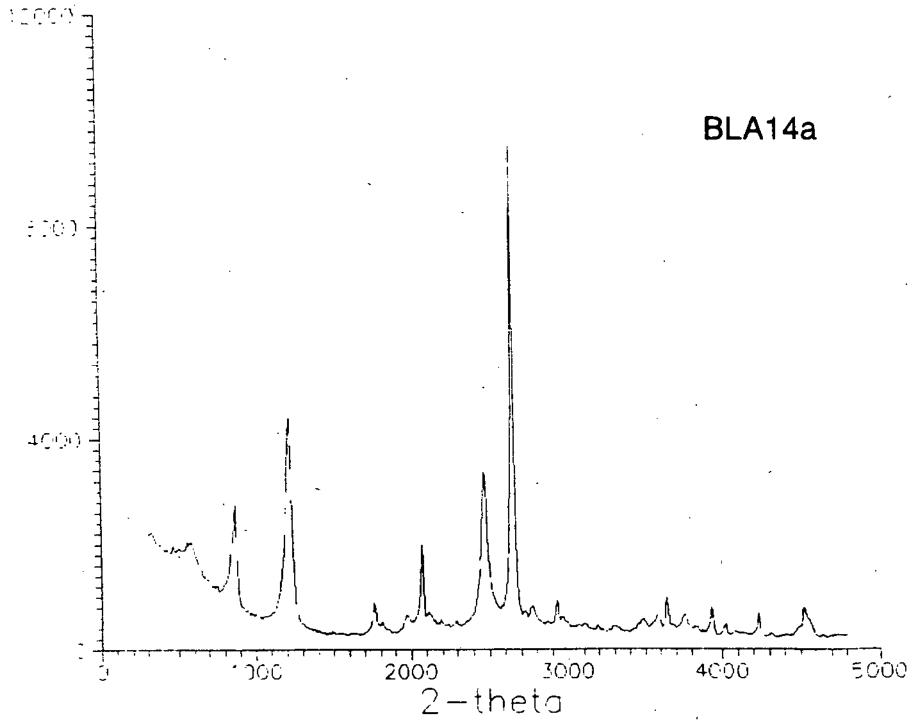
APPENDIX 11: X-RAY DIFFRACTION PLOTS OF SOME SELECTED REPRESENTATIVE CLAY FRACTIONS OF SAMPLES

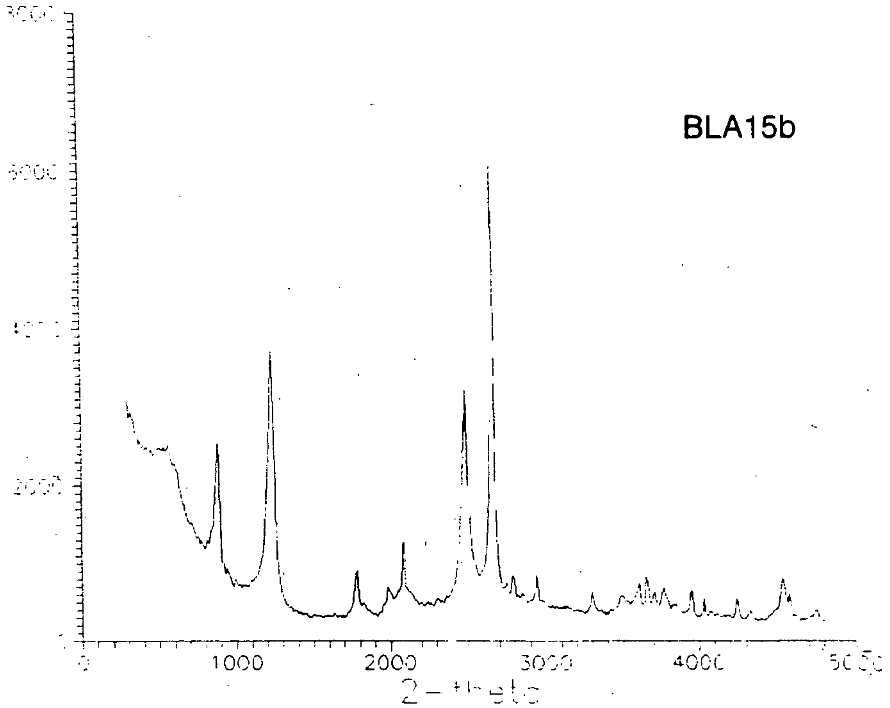


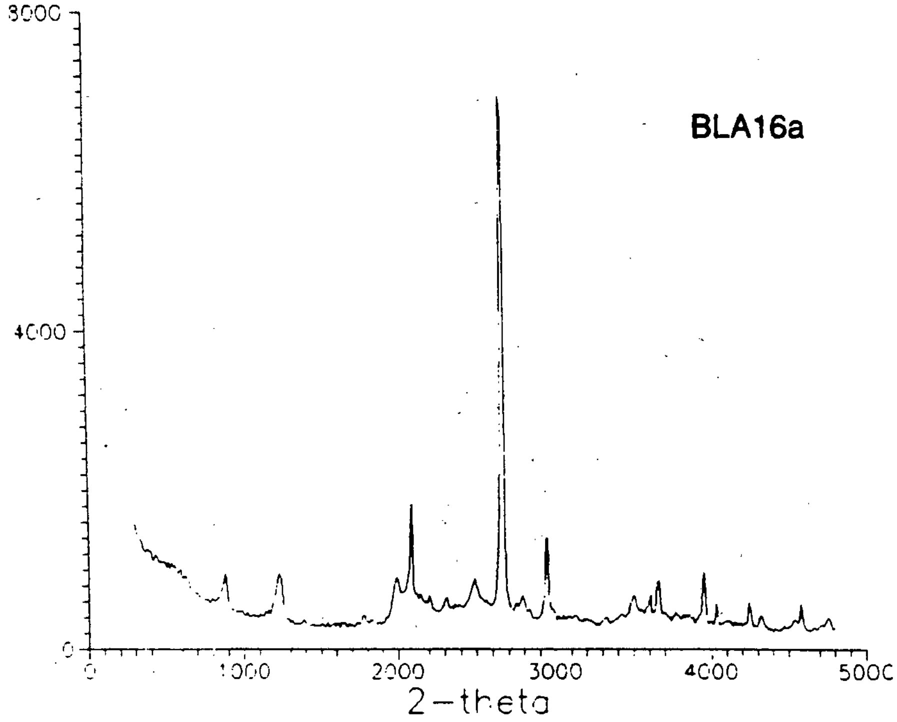


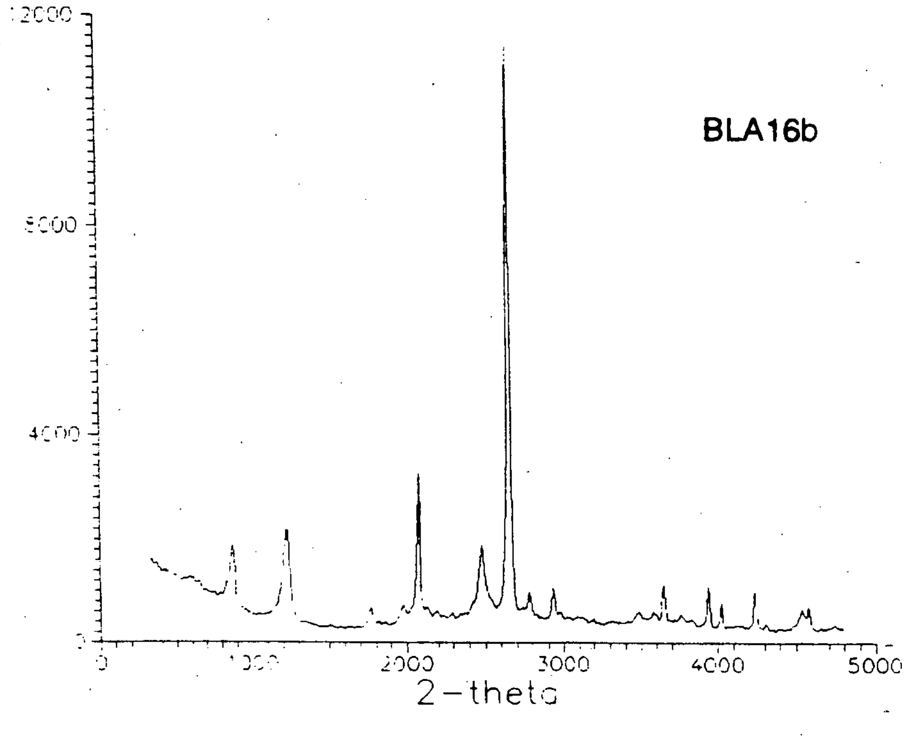

Els6
6000
4000
2000
0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
50
2-theta


BLA13a
16000
8000
0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
50
2-theta


BLA14a
12000
8000
4000
0
0
1000
2000
3000
4000
5000
2-theta


BLA15b
8000
6000
4000
2000
0
0
1000
2000
3000
4000
5000
2-theta


BLA16a
8000
4000
0
0
1000
2000
3000
4000
5000
2-theta


BLA16b
12000
8000
4000
0
0
1000
2000
3000
4000
5000
2-theta

APPENDIX 12: DETAILS OF MICROPHOTOGRAPHY EQUIPMENT

Microscope:	Multiphot attachment, with extended focal length, on bellows system.
Camera:	Nikon model F2.
Film:	Kodak Vericolour.
ASA:	160.
Shutter speed:	Ranging from 2 seconds to 30 seconds.
Linear magnification:	Ranging from 6 times to 20 times.

APPENDIX 13: ALL UNIVARIATE PARAMETRIC ANALYSIS OF VARIANCE P-VALUES FOR EACH VARIABLE IN EACH GROUP PAIRING (BMDP7D)

Group Pairing	% Gravel	% Sand	% Silt	% Clay	Sand Fraction Parameter Values					
					Mode	Median	Mean	Sorting	Skewness	Kurtosis
B-V	0,011	0,009	1,000	1,000	0,533	0,526	0,484	0,204	0,677	0,545
B-E	0,161	0,627	0,061	0,049	0,000	0,000	0,000	0,190	0,130	0,117
B-U	0,016	0,013	1,000	1,000	0,321	0,509	0,511	0,631	0,663	0,955
B-M	0,017	0,013	1,000	1,000	0,009	0,021	0,022	0,875	0,976	0,799
B-L	0,019	0,015	1,000	1,000	0,004	0,003	0,002	0,205	0,563	0,267
B-X	0,857	0,071	0,000	0,000	0,000	0,000	0,000	0,002	0,080	0,000
V-E	0,180	0,011	0,022	0,016	0,000	0,000	0,000	0,002	0,020	0,225
V-U	0,792	0,784	1,000	1,000	0,592	0,891	0,947	0,473	0,356	0,589
V-M	0,744	0,734	1,000	1,000	0,014	0,039	0,047	0,300	0,717	0,776
V-L	0,710	0,699	1,000	1,000	0,006	0,005	0,004	0,769	0,777	0,473
V-X	0,008	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,011	0,000
E-U	0,178	0,019	0,061	0,049	0,002	0,003	0,004	0,066	0,303	0,133
E-M	0,174	0,020	0,072	0,059	0,294	0,295	0,349	0,153	0,138	0,222
E-L	0,177	0,024	0,088	0,073	0,576	0,922	0,918	0,011	0,046	0,839
E-X	0,170	0,009	0,016	0,020	0,001	0,001	0,001	0,025	0,739	0,003
U-M	0,948	0,946	1,000	1,000	0,086	0,091	0,093	0,759	0,652	0,841
U-L	0,907	0,903	1,000	1,000	0,042	0,017	0,014	0,408	0,327	0,290
U-X	0,014	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,199	0,000
M-L	0,958	0,956	1,000	1,000	0,701	0,431	0,385	0,278	0,594	0,399
M-X	0,015	0,000	0,000	0,000	0,000	0,000	0,000	0,002	0,087	0,000
L-X	0,018	0,000	0,000	0,000	0,001	0,007	0,014	0,000	0,028	0,011

APPENDIX 14: ALL UNIVARIATE NONPARAMETRIC (MANN-WHITNEY) P-VALUES FOR EACH VARIABLE IN EACH GROUP PAIRING (BMDP3S)

Group pairing	% Gravel	% Sand	% Silt	% Clay	Sand fraction parameter values					
					Mode	Median	Mean	Sorting	Skewness	Kurtosis
B-V	0,004	0,004	1,000	1,000	0,769	0,560	0,540	0,079	0,793	0,770
B-E	0,337	0,946	0,037	0,037	0,013	0,006	0,006	0,259	0,094	0,005
B-U	0,015	0,015	1,000	1,000	0,671	0,674	0,599	0,462	0,528	1,000
B-M	0,005	0,005	1,000	1,000	0,048	0,032	0,037	0,908	0,907	0,816
B-L	0,004	0,004	1,000	1,000	0,121	0,053	0,052	0,173	0,518	0,033
B-X	0,274	0,189	0,000	0,000	0,000	0,000	0,000	0,076	0,395	0,002
V-E	0,091	0,002	0,003	0,003	0,001	0,001	0,002	0,001	0,002	0,009
V-U	1,000	1,000	1,000	1,000	0,195	0,484	0,541	0,065	0,054	0,231
V-M	0,253	0,253	1,000	1,000	0,007	0,016	0,019	0,074	0,483	0,524
V-L	0,326	0,326	1,000	1,000	0,017	0,023	0,021	0,805	0,916	0,079
V-X	0,324	0,000	0,000	0,000	0,000	0,000	0,000	0,013	0,277	0,002
E-U	0,104	0,006	0,037	0,037	0,017	0,005	0,005	0,065	0,124	0,008
E-M	0,044	0,004	0,049	0,049	0,330	0,411	0,411	0,232	0,072	0,014
E-L	0,057	0,006	0,067	0,067	0,534	1,000	0,805	0,017	0,025	0,772
E-X	0,831	0,099	0,019	0,010	0,011	0,010	0,027	0,198	0,857	0,207
U-M	0,361	0,361	1,000	1,000	0,026	0,011	0,008	0,486	0,562	0,601
U-L	0,391	0,391	1,000	1,000	0,242	0,093	0,071	0,331	0,136	0,032
U-X	0,323	0,001	0,000	0,001	0,000	0,001	0,000	0,082	0,417	0,005
M-L	1,000	1,000	1,000	1,000	0,943	0,886	0,668	0,085	0,519	0,053
M-X	0,158	0,001	0,000	0,000	0,002	0,009	0,009	0,076	0,374	0,005
L-X	0,217	0,001	0,001	0,001	0,031	0,055	0,134	0,017	0,261	0,222

APPENDIX 15: ALL UNIVARIATE PARAMETRIC T-TEST P-VALUES FOR EACH VARIABLE IN EACH GROUP PAIRING (BMDP3D)

Group pairing	% Gravel	% Sand	% Silt	% Clay	Sand fraction parameter values					
					Mode	Median	Mean	Sorting	Skewness	Kurtosis
B-V	0,002	0,002	1,000	1,000	0,016	0,261	0,309	0,000	0,114	0,672
B-E	0,070	0,140	0,001	0,005	0,872	0,335	0,340	0,688	0,231	0,982
B-U	0,003	0,003	1,000	1,000	0,005	0,040	0,041	0,074	0,095	0,977
B-M	0,005	0,005	1,000	1,000	0,167	0,716	0,825	0,455	0,306	0,466
B-L	0,007	0,007	1,000	1,000	0,507	0,075	0,052	0,323	0,512	0,669
B-X	0,640	0,980	0,002	0,000	0,212	0,304	0,134	0,027	0,060	0,004
V-E	0,025	0,001	0,000	0,000	0,005	0,011	0,016	0,000	0,635	0,631
V-U	0,248	0,248	1,000	1,000	0,140	0,066	0,048	0,018	0,942	0,625
V-M	0,251	0,251	1,000	1,000	0,775	0,619	0,562	0,003	0,769	0,800
V-L	0,187	0,187	1,000	1,000	0,001	0,000	0,000	0,001	0,446	0,983
V-X	0,000	0,000	0,000	0,000	0,127	0,009	0,002	0,000	0,001	0,000
E-U	0,003	0,000	0,001	0,005	0,003	0,003	0,004	0,070	0,596	0,957
E-M	0,004	0,000	0,002	0,008	0,099	0,199	0,269	0,312	0,939	0,472
E-L	0,004	0,000	0,004	0,014	0,615	0,319	0,239	0,261	0,688	0,671
E-X	0,012	0,104	0,784	0,779	0,130	0,899	0,530	0,035	0,003	0,000
U-M	0,802	0,802	1,000	1,000	0,228	0,135	0,120	0,318	0,697	0,288
U-L	0,139	0,139	1,000	1,000	0,000	0,000	0,000	0,312	0,306	0,542
U-X	0,001	0,001	0,002	0,000	0,006	0,003	0,001	0,001	0,010	0,004
M-L	0,285	0,285	1,000	1,000	0,040	0,050	0,055	0,842	0,687	0,777
M-X	0,001	0,003	0,004	0,001	0,461	0,185	0,112	0,011	0,025	0,004
L-X	0,002	0,004	0,007	0,002	0,022	0,391	0,489	0,010	0,051	0,009

APPENDIX 16: MULTIVARIATE CANONICAL DISCRIMINANT ANALYSIS PLOT FOR ALL SAMPLES (SAS CANDISC)

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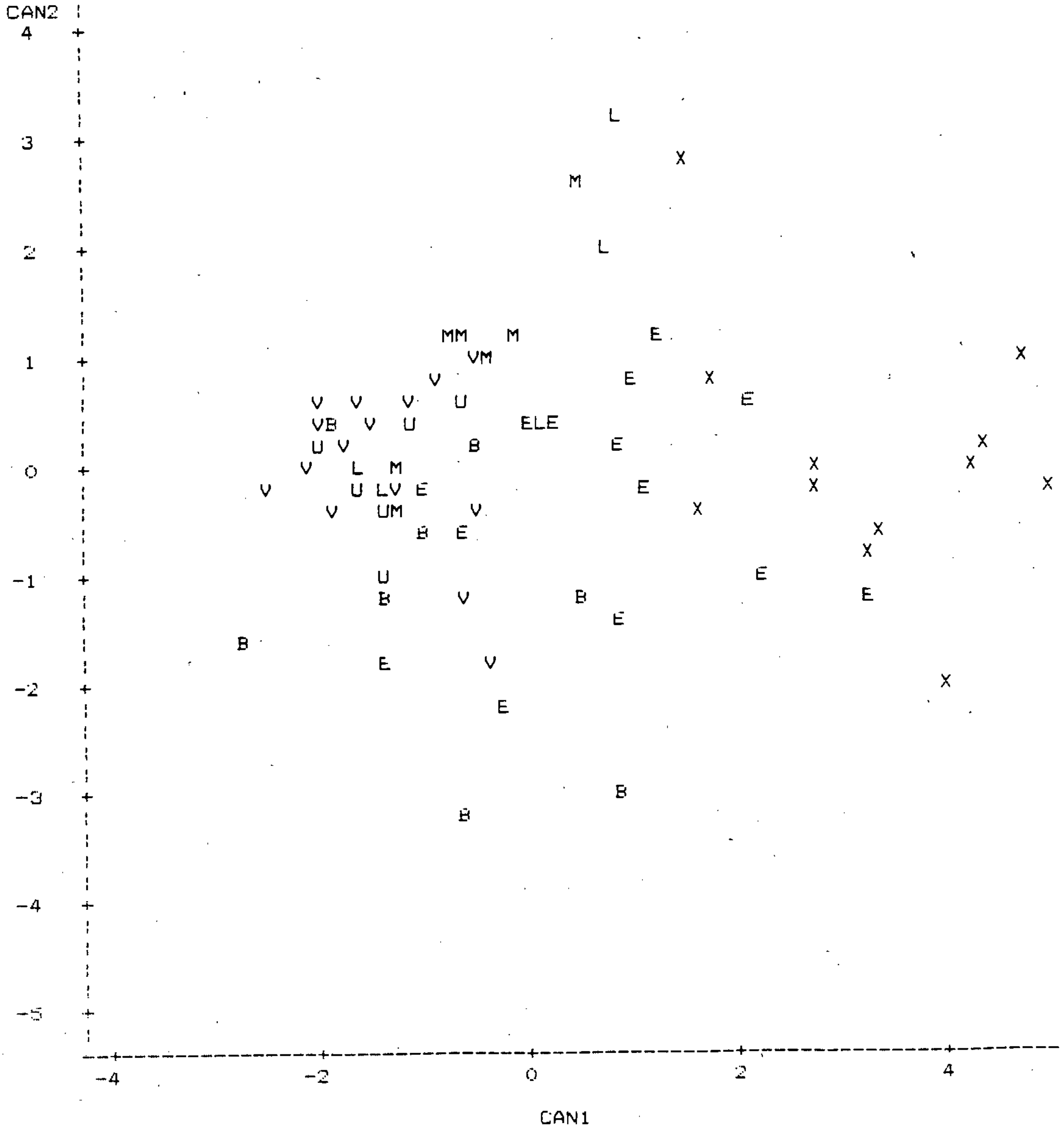
SAS

PLOT OF CAN2*CAN1     SYMBOL IS VALUE OF SAMPLE
```



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NOTE:          5 OBS HIDDEN
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APPENDIX 17 : MULTIVARIATE FACTOR ANALYSIS RESULTS (BMDP4M) - SORTED FACTOR LOADINGS OF VARIABLES ON FACTORS

Variable		Factor 1	Factor 2
in entire sample	Gravel %	0,078	0,916
	Sand %	-0,431	-0,856
	Silt %	0,757	-0,021
	Clay %	0,748	0,123
in sand fraction	Mode	0,930	-0,240
	Median	0,911	-0,325
	Mean	0,893	-0,361
	Sorting	0,551	0,628
	Skewness	-0,466	-0,157
	Kurtosis	0,679	-0,052

APPENDIX 18: FACTOR ANALYSIS SCORES FOR ALL SAMPLES (BMDP4M)

Group	Sample	Factor 1	Factor 2
B	BLA 1	-1,655	-0,878
B	BLA 3	-0,091	-0,587
B	BLA 5	-0,854	-0,422
B	BLA 7	-1,599	-0,625
B	BLA 9	-0,911	-0,514
B	KRO 1	-1,752	-0,232
B	KRO 4	0,180	-0,444
B	KRO 6	0,104	-0,680
V	VYG 1	-0,320	-0,132
V	VYG 3	-0,337	-0,413
V	VYG 5	-0,844	-0,177
V	VYG 7	-0,820	-0,469
V	VYG 9	-0,847	-0,382
V	VYG 10	-1,194	-0,356
V	VYG 12	-0,932	-0,401
V	BLO 2	-0,841	-0,518
V	BLO 4	-0,529	-0,547
V	BLO 5	-0,803	-0,368
V	BLO 6	-0,921	-0,431
V	BOK 1	0,363	-0,627
V	BOK 3	0,895	-0,674
V	JAK 1	-0,594	-0,396
V	JAK 3	-1,060	-0,421
V	KAL 2	-0,392	-0,626
V	KAL 3	-0,367	-0,095
E	ELS 3	-1,215	3,294
E	ELS 5	0,079	2,418
E	ELS 6	0,250	1,789
E	ELS 8	1,144	-0,081
E	ELS 9	-0,140	-0,512
E	ELS 11	0,590	-0,073
E	ELS 13	1,149	-0,062
E	ELS 14	0,947	-0,547
E	ELS 17	0,856	-0,276
E	ELS 19	-0,113	-0,715
E	ELS 23	-0,878	-0,663
E	ELS 25	-0,259	-0,150
E	ELS 28	-0,160	-0,385
E	ELS 29	0,948	-0,700

Group	Sample	Factor 1	Factor 2
U	VYG 13a	-0,437	-0,242
U	VYG 13b	0,370	-0,655
U	VYG 14a	0,126	-0,539
U	VYG 14b	-0,699	-0,324
U	VYG 14c	-0,593	-0,374
U	VYG 15a	-0,579	-0,343
U	VYG 15b	-0,137	-0,331
U	VYG 15c	0,111	-0,546
M	VYG 16a	0,064	-0,409
M	VYG 16b	-0,678	-0,116
M	VYG 16c	0,208	-0,116
M	VYG 17a	0,263	-0,495
M	VYG 17b	0,253	-0,161
M	VYG 17c	0,087	-0,185
M	VYG 17d	0,435	0,527
L	BLA 10a	-0,084	-0,439
L	BLA 10b	-0,354	-0,059
L	BLA 10c	0,438	0,633
L	BLA 11a	-0,145	-0,465
L	BLA 11b	0,928	-0,133
L	BLA 11c	0,897	0,358
X	BLA 12a	0,665	0,500
X	BLA 12b	-1,078	0,431
X	BLA 12c	2,378	-0,377
X	BLA 13a	0,233	2,373
X	BLA 13b	-0,903	4,544
X	BLA 14a	0,713	0,626
X	BLA 14b	3,456	-1,575
X	BLA 14c	0,665	0,971
X	BLA 15a	0,768	0,890
X	BLA 15b	3,453	0,089
X	BLA 16a	2,303	1,927
X	BLA 16b	-0,202	2,090

APPENDIX 19 : CORRELATION MATRIX FOR VARIABLES - DERIVED FROM MULTIVARIATE FACTOR ANALYSIS (BMDP4M) AND MULTIVARIATE PRINCIPAL COMPONENT ANALYSIS (SAS PRINCOMP)

Variable	Gravel	Sand	Silt	Clay	Mode	Median	Mean	Sorting	Skewness	Kurtosis
Gravel	1,000	-	-	-	-	-	-	-	-	-
Sand	-0,880	1,000	-	-	-	-	-	-	-	-
Silt	-0,075	-0,403	1,000	-	-	-	-	-	-	-
Clay	0,003	-0,470	0,958	1,000	-	-	-	-	-	-
Mode	-0,085	-0,210	0,607	0,582	1,000	-	-	-	-	-
Median	-0,153	-0,142	0,601	0,558	0,982	1,000	-	-	-	-
Mean	-0,182	-0,117	0,606	0,557	0,974	0,997	1,000	-	-	-
Sorting	0,483	-0,640	0,385	0,483	0,352	0,262	0,215	1,000	-	-
Skewness	-0,143	0,165	-0,068	-0,083	-0,397	-0,353	-0,290	-0,476	1,000	-
Kurtosis	0,075	-0,202	0,301	0,252	0,589	0,620	0,595	0,266	-0,636	1,000

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