# WATER RESEARCH COMMISSION

# SEDIMENT TRANSPORT IN RIVERS AND RESERVOIRS
# -
# A SOUTHERN AFRICAN PERSPECTIVE

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**WATER RESEARCH COMMISSION**

**RESEARCH PROJECT - PREPARATION OF AN OVERVIEW DOCUMENT ON SEDIMENT TRANSPORT IN SOUTHERN AFRICA, INCLUDING REVISION OF THE SEDIMENT YIELD MAP OF SOUTHERN AFRCA**

# OVERVIEW DOCUMENT: SEDIMENT TRANSPORT IN RIVERS AND RESERVOIRS - A SOUTHERN AFRICAN PERSPECTIVE

**by**

**A Rooseboom**

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**Sigma Beta Consulting Engineers**
**P O Box 274**
**STELLENBOSCH**
**7599 SOUTH AFRICA**

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## ABSTRACT

This document provides a southern African overview on sediment transport in rivers and reservoirs.

The various approaches to sediment sampling and data processing techniques during the past sixty years are described.

A fundamental treatise on open channel flow and associated hydraulic sediment transport processes, based on the principle of conservation of stream power is given. This approach provides a logical and comprehensible description of the processes and has the advantage that it was developed specifically for open channel flow, unlike most other approaches which were adopted from aeronautical or pipe flow theory.

Observed sediment yield patterns in southern African rivers are described, as well as methods to make meaningful estimates of average annual sediment loads.

A summary is given of work done to develop the new (1992) sediment yield map of southern Africa. This includes the sub-division of the region into sub-regions of equal sediment yield potential and the use of various techniques in an attempt to quantify the variability which is encountered in sediment yields.

The methodology which is to be used to obtain estimates of sediment yield values for ungauged catchments by means of the new sediment yield map is described.

A comprehensive bibliography on southern Africa sediment transport and related subjects is included.

## ACKNOWLEDGEMENTS

I wish that it was possible to give personal recognition to all those who have contributed to make this publication possible. The list would have to start with the names of those who initiated sediment sampling and research in South Africa more than 60 years ago and would include the names of those who diligently continued these efforts, sometimes under difficult circumstances.

The main recognition should go to the Department of Water Affairs. Not only has this department and its predecessors been responsible for collecting most of the information which is available but it also sponsored my earlier attempts in analyzing the data and trying to understand the processes. I am specially indebted to (Dr) J P Kriel and (Prof) W J R Alexander who as Secretary of Water Affairs and Head of the Hydrology Division respectively provided me with these opportunities.

This document together with the 1992 sediment yield map were sponsored by the Water Research Commission (Project Leader Mr H Maaren) to whom I wish to express my sincere gratitude.

Apart from those mentioned in the document accompanying the sediment yield map, special thanks are due to:

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The members of the Steering Committee:

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## LIST OF SYMBOLS

| | |
|---|---|
| $A$ | area |
| $A$ | empirical coefficient |
| $A_1 \ldots A_n$ | uniquely defined sub-catchment areas |
| $A_H$ | subcatchment area with highest sediment yield potential |
| $A_m$ | subcatchment area with medium sediment yield potential |
| $A_L$ | subcatchment area with lowest sediment yield potential |
| $A_T$ | total catchment area |
| $B$ | empirical coefficient |
| $C$ | runoff coefficient |
| $C$ | sediment concentration |
| $\overline{C}$, $C_s$ | average sediment concentration |
| $C_a$ | reference concentration at distance a from bed |
| $C_d$ | drag coefficient |
| $C_h$ | Chézy roughness coefficient |
| $d$ | particle diameter |
| $D$ | depth of flow |
| $e$ | base of natural logarithms |
| $f$ | Darcy Weisbach friction factor |
| $F$ | Mean shearing force |
| $F_H$ | high yield potential factor |
| $F_m$ | medium yield potential factor |
| $F_L$ | low yield potential factor |
| $g$ | gravitational constant |
| $i$ | rainfall intensity |
| $I$ | moment of inertia |

| | |
|---|---|
| $k$ | absolute surface roughness |
| $k_1$, $k_2$ ... $k_n$ | empirical coefficients |
| $l$ | mixing length |
| $L$ | length of catchment strip |
| $L$ | distance down a slope at which erosion will begin |
| $m$ | mass, of small element |
| $n$ | Manning roughness coefficient |
| $p$ | pressure |
| $P$ | power |
| $\overline{P}$ | average power |
| $q$ | discharge per unit width |
| $q_{cr}$ | critical discharge at initiation of sediment movement |
| $q_s$ | sediment discharge per unit width |
| $Q_s$ | total annual catchment sediment yield |
| $r$ | radius |
| $R$ | radius |
| $R_o$ | outer radius of boundary eddies |
| $R_e$ | Reynolds number |
| $R_{eff}$ | effective radius |
| $S$ | energy slope |
| $S_s$ | slope of surface line |
| $v$ | average point velocity |
| $\overline{v}$ | average velocity |
| $\overline{v}_o$ | velocity of centre of rotation |
| $v_{ss}$ | particle settling velocity |
| $V_t$ | volume of sediment after t years |

| | |
|---|---|
| $V_w$ | storage volume of reservoir |
| $V_{50}$ | volume of sediment deposit after 50 years |
| $x$ | distance in direction of flow |
| $y$ | distance perpendicular to river bed |
| $y_o$ | distance from mathematical boundary where velocity = 0 |
| $y_1$ | distance from mathematical boundary where transition from laminer to turbulent flow takes place |
| $Y_c$ | estimated catchment sediment yield value |
| $Y_s$ | standardized sediment yield value |
| $Z$ | distance from eddy centre |
| $Z$ | horizontal distance per unit vertical distance |
| $Z$ | exponent in the suspension distribution equation |
| $Z_1$ | exponent in the suspension distribution equation |
| $\alpha$ | empirical coefficient |
| $\alpha$ | angle |
| $\alpha_1 \ldots \alpha_n$ | sediment yields per unit catchment area |
| $\beta$ | empiral coefficient |
| $\rho$ | fluid density |
| $\rho_s$ | sediment density |
| $\tau$ | shear stress |
| $\tau_o$ | boundary shear stress |
| $\tau_o$ | acting bed shear stress |
| $\tau_{cr}$ | critical bed shear stress |
| $\mu$ | dynamic viscosity |
| $\nu$ | kinematic viscosity |
| $\kappa$ | Von Karman coefficient |

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## DEFINITIONS

Following a suggestion by a colleague, I have prepared a number of definitions which might be useful to readers who are not familiar with some important terms. These terms which are often used in describing erosion and sediment transport have not been uniquely defined and it has proved quite a challenge to try and provide clear definitions for them.

Colloidal sediment transport

Very small sediment particles are carried in colloidal suspension when they are kept in suspension due to the fact that they are electrically charged.

Density currents (associated with sediments)

Inflows containing high sediment concentrations which proceed along the beds of reservoirs underneath water bodies already contained within the reservoirs. Density currents occur mainly where moderately large inflows with high sediment loads enter deep water bodies along steep bed slopes. As such conditions are not common in South African reservoirs, sediment-induced density currents do not play significant roles in existing South African reservoirs.

Erosion: (From the Latin rodere: to gnaw)

Three main types of erosion can be identified in South Africa:
fragmentation erosion
hydraulic erosion
wind erosion

Fragmentation erosion

Detachment of sediment particles from soil and rock masses through physical and chemical processes. Natural processes include weathering, trampling etc. whereas mechanical processes include agricultural activities such as ploughing etc. In southern Africa it is often the sediments that are made available through fragmentation erosion rather than through direct hydraulic erosion or direct wind erosion that form the bulk of sediment loads in rivers.

Hydraulic erosion

Detachment of sediment particles resulting from the shear forces being exerted by flowing water along the contact zone between water and soil or rock masses.

Reservoir trap efficiency

That percentage of the average sediment load which enters a reservoir that is trapped within the reservoir.

Sediment

Elements with higher densities than that of the transporting medium (e.g. water or air) which are small enough to be entrained and transported by the given transporting medium.

Sediment load

The mass or volume of sediment which is carried past a given flow section during a specific period.

Sediment yield

The nett mass or volume of sediment which is removed from a catchment during a specific period of time.

Average yield

= ($\Sigma$ loads transported out of the catchment - $\Sigma$ loads transported into the catchment)/catchment area.time

Average yield is normally expressed in terms of $t/km^2$.annum.

Turbulent transport

Transportation of sediment through turbulent suspension or semi-suspension - the major transporting mechanism in South African rivers and reservoirs, responsible for more than 96% of the sediment being carried in most cases.

Wind erosion

Similar to hydraulic erosion except that the shear stresses are generated as a result of the velocity gradients which develop in flowing air.

Wind transport

Transportation of sediment in suspension (so-called suspended load) or semi-suspension (so-called bed-load) by winds. The relative importance of this intermediatory agent in transporting sediments has generally been underestimated in the past.

Wind or aeolian transport possesses the highest transporting capacity over high-lying areas where the water or hydraulic transporting capacity is lowest. After having entrained sediment particles winds tend to deposit these particles in low-lying areas available for transport by water run-off at some later stage.

# 1. INTRODUCTION

A need has long been perceived for a southern African overview on sediment transport in rivers and reservoirs. A large volume of data and experience has been built up locally over a period of more than 60 years.

Various pieces of information, including some which were originally written in Afrikaans and others which have not been properly documented, have been brought together. It is hoped that this document will serve as a useful summary of the insight which has been gained and of the information which has been collected.

It has been decided to document how early sediment sampling was done, how the samples were processed and how the results were analysed so that future generations will be able to compare past records with those of the future.

A relatively complete theoretical treatise on sediment transport hydraulics has been included for two reasons:

(i) The resulting equations have been used successfully in various practical applications.

(ii) It has been found that the approach which has been followed is more effective in describing the phenomena than many of the classical, largely empirical, theories which have understandably been developed along such circuitous routes.

Chapters 4 and 5 deal with sediment transport and yield patterns which have been observed in southern Africa. Both the variability of sediment loads with time as well as the spatial variability of yields are discussed in terms of some 60 years of record.

A comprehensive bibliography containing more than 600 references relating to erosion and sediment production in southern Africa has been included for further reference.

It is believed that most of the original objectives of the project to provide an overview document covering

(i) sediment transport theory
(ii) sediment load measurements
(iii) sediment yield patterns
(iv) future research and monitoring needs

have been met.

This document should be read in conjunction with its sister publication:

"The development of the new sediment yield map for southern Africa (Rooseboom et al. 1992) which was prepared in parallel with this document.

Whereas early interest in riverine sediment transport was focussed mainly on reservoir sedimentation, there has recently been growing broader interest particularly from those involved in environmental studies. This document will hopefully also serve these broader interests.

# 2. HISTORICAL BACKGROUND

## 2.1 Introduction

Early attempts to quantify the sediment loads of southern African rivers were prompted mainly by the potential threat that sedimentation posed to reservoirs.

As far as could be ascertained, rapid sedimentation of Camperdown Reservoir in Natal led to the first formal investigations into reservoir sedimentation. According to the archives of the Mgeni Water Board, Camperdown Dam was completed on the farm Killarney Isle in 1901 to augment the water supply of the Umlaas River. By 1923 the capacity of the reservoir had decreased by 40% and by 1935 the reservoir was completely "silted up" in spite of the installation of a "by-passing system involving sluice gates" in 1924. The current significance of reservoir sedimentation has been highlighted by Braune and Looser (1989) and by Jordaan (1989).

South Africa is in the fortunate position that its Department of Water Affairs and the department's predecessors started to build up information on the sediment loads of southern African rivers at an early stage.

Ad hoc river sediment sampling was initiated in 1919 and regular sampling programmes (daily sampling) was initiated at a number of stations during 1928 - 1929. Through the years the emphasis in monitoring of sediment loads has shifted from daily stream sampling to regular resurveying (every 10 years) of existing reservoirs to record sediment accumulation rates.

Most of the original stream sampling data collected up to 1970 have unfortunately been lost and the procedures which were used in processing the samples as well as the data have not been widely published. It has therefore been decided to document both the methodology as well as the impressions gained from working with the original data in order that future generations will be able to draw comparisons between old and new results.

## 2.2 Early stream sampling attemps

Attempts to determine the sediment loads of a few rivers started around 1919 (Warren, 1922; Van Warmelo 1922a, 1922b, 1922c; Rand Water Board, 1924).

These attempts were of an ad hoc nature and the method of determining sediment concentrations was rather crude. Sampling consisted of submerging a 4 gallon (18 l) paraffin can in the stream to fill. The can was then stored and after the sediments had settled out the thickness of the deposited layer would be measured and converted into a concentration value. Prior to 1928 concentrations were determined on such an infrequent basis that no meaningful conclusions can be drawn from them. Only after regular sampling was started at the Barrage on the Vaal River and a year later at other stations were continuous records obtained that would prove to be of great value.

## 2.3 Regular stream sampling

### 2.3.1 Sampling techniques

The sampling techniques which were used changed little during the period (1929 - 1971) when most of the daily samples were collected.

According to the original sampling instructions the person taking the sample was instructed to:

(i) daily (at 08h00) take a bottle from the storage crate and remove its cap.

(ii) submerge it 1 ft (300 mm) below the stream surface and allow it to run full. This proved to be very difficult when rivers were in flood and when it was cold. The bottle cap was then replaced and the bottle returned to the crate. In order to limit algal growth the bottles had to be stored in dark, cool spaces. Initially, standard milk bottles were used. These were replaced by plastic bottles in later years.

(iii) After all 14 the bottles in a crate were filled, the wooden crate was sent to Pretoria by rail where the samples were analysed. Unfortunately the original log books containing the sampling information, including the written comments of the persons taking the samples, have been lost. The written comments related mainly to visual observations concerning the colour of the river. One main impression which has remained with the author after working through these log books was the fact that the observers often were not able to draw correct conclusions regarding sediment loads from changes in colour. It became clear from comparing these remarks with the sediment concentrations which were subsequently determined for the samples that the colour of a stream tends to be an unreliable indicator of the sediment load.

Apart from regular sampling performed by means of the bottle sampling method, turbidity meters were used on a limited scale (James, 1969).

Turbidisonde sampling was undertaken by W J R Alexander at Bethulie (Orange River) during 1967 - 1969 and pumped sampling by Rooseboom (1975) on the Verwoerd Reservoir during the early 1970's in order to determine the representativeness of bottle samples (See 2.3.3).

### 2.3.2 Processing of bottle samples

Bottle samples were railed to Pretoria in their special crates for processing where the sediment concentration of each incoming sample was determined in the Department of Water Affairs' Laboratories.

Following a period of rest during which the sediments in a sample were allowed to settle out, the major proportion of the water in the sample would be decanted. The remaining water would then be driven off by heating. Filtration was rarely used to seperate the water from the sediments in the sample because filters tended to become clogged due to the fineness of most sediment samples.

The concentration which was subsequently calculated from the mass of the dried sediment and the mass of the original sample would normally be expressed as a percentage by mass. Initially, concentrations were expressed in terms of ounces per cubic foot. This unit differs from percentage by mass by a factor ten. It was thus easy to convert the one unit into the other but the existence of both units in earlier records led to confusion which has hopefully been sorted out completely in deriving the results which are included in this document.

It should be mentioned that because of the fact that a large proportion of the water content of each sample was decanted, the sediment concentrations which were determined include small fractions of the dissolved solids contained in the samples. Where dissolved solid contents were determined separately in later years, these concentrations tended to be much smaller than the sediment concentrations.

Up to 1971 grain size analyses were performed by sieve above 0,03 mm and by means of the hydrometer method for smaller particles. Because of the fact that 25 g of sediment was required in standard hydrometer analyses, the sediment from a number of samples had to be accumulated to be able to do a grain size analysis. Fortunately it was found that size distribution did not vary greatly with time.

The grading analyses proved to be useful for different purposes. One less obvious use was to determine the upper limit of the possible contribution of "bed load" to the so-called un-monitored load in calculating the "total load". By comparing the grading analyses of the bottle samples with those of the in situ bed material as well as soil samples from the catchment it was possible to prove that the so-called "bed load" could be no more than a limited fraction of the suspended load as represented by the bottle samples.

### 2.3.3 Representativeness of bottle samples

The question obviously arises as to whether single daily sediment samples, supposedly taken 300 mm below the surface, can be representative of the load of a stream which is many metres wide and deep.

It will be shown in Chapter 3 that when the settling velocities of particles being transported are small, relative to the shear velocity of the stream, sediment concentrations tend to vary only slightly across the stream. From a monitoring point of view it is thus fortunate that the sediment particles carried by southern African rivers at the points where stream sampling was undertaken tend to be small with a large proportion

< 0,2 mm in diameter. Because of this, it is possible to convert the recorded bottle concentrations into mean concentrations for the total stream cross sections by applying correction factors.

The most comprehensive comparison (Rooseboom, 1975) of bottle sample results with those obtained by other means was based on sampling undertaken by W J R Alexander at Bethulie Bridge during 1967 - 1969. Samples were obtained at different depths in the Orange River for different discharges by means of a Neyrpic Turbidisonde and the results were compared with those obtained by means of standard bottle samples.

It was found (Rooseboom, 1975) that concentrations varied little with depth. Figure 2.1 contains typical results of these measurements and it was possible to determine an average correction factor to convert bottle samples into weighed average concentrations to obtain total sediment loads. For Bethulie Bridge this factor came out at 1,25 which means that the weighed average concentrations are 25% higher than those determined from bottle samples (Figure 2.2).

Further tests were performed by the author on the Verwoerd Reservoir where samples were obtained by means of pumping samplers, Hydrobios flasks and the bottle method. It appeared from these tests that the bottle method led to underestimation of sediment concentrations. This is probably due to segregation of sediment particles which takes place as a bottle fills intermittently due to escaping air.

It was interesting to note that the correction factor of 1,25 agrees with the so-called bed load factor which was used earlier within the Department of Water Affairs for converting bottle concentrations into average concentrations. This factor was apparently taken over

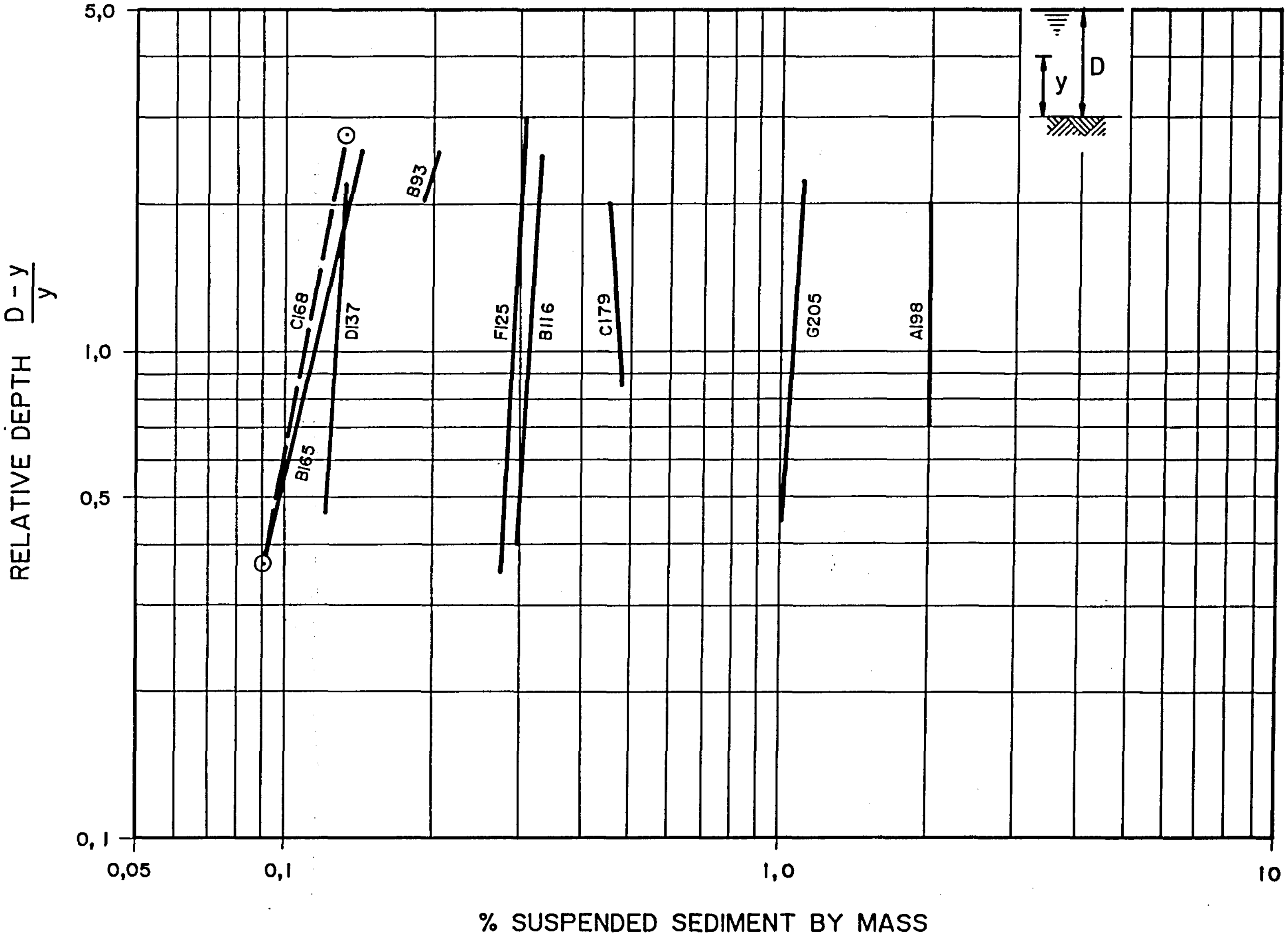



FIG 2.1

VARIATION IN SUSPENDED SEDIMENT CONCENTRATION WITH DEPTH:
ORANGE RIVER AT BETHULIE BRIDGE (D3M02)

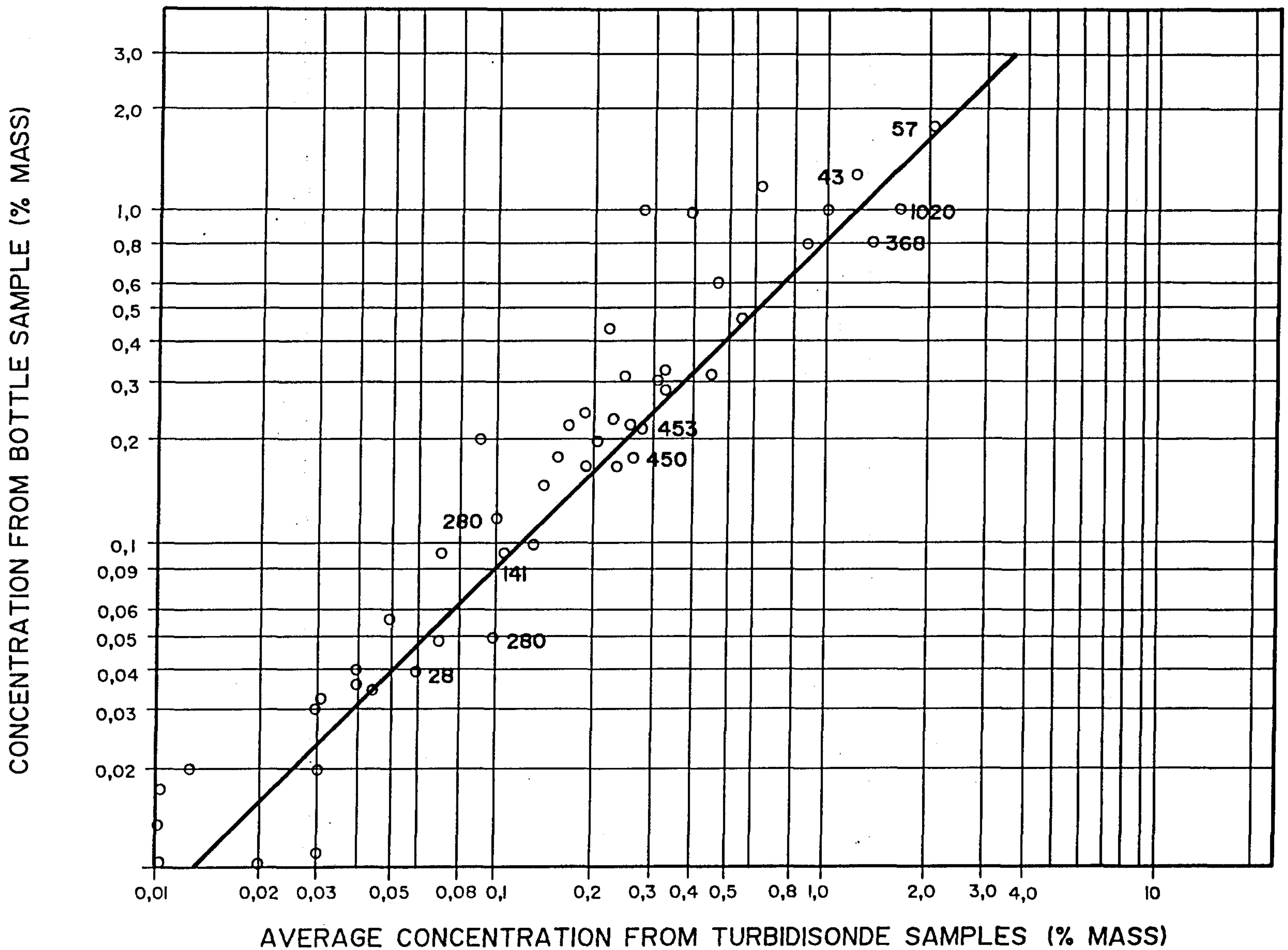



FIG 2.2 : COMPARISON OF BOTTLE AND AVERAGED TURBIDISONDE CONCENTRATIONS : ORANGE RIVER

from American information and was supposed to correct for that part of the load which is carried as "bed load" and which supposedly consists of coarser particles which are not represented in the suspended load. Our own analyses of suspended load samples indicated that particle size distributions were practically constant over the full depth of the Orange River at Bethulie. With the fine sediments being carried in such homogeneous suspension it becomes meaningless to differentiate between "suspended load" and "bed load". Although the so-called "bed load" correction factor of 1,25 therefore appears to be correct, it provides for the variations in suspended sediment concentration with depth as well as the tendency with bottle samples to underrepresent actual concentrations. The latest ICOLD guidelines on sedimentation control of reservoirs (ICOLD, 1989) contains revised "bed load" correction factors.

Typical suspended concentration values recorded in South African rivers are as follows:

Even with very low flow velocities within reservoirs, concentrations are rarely lower than 0,001% by mass (10 p.p.m.). Under flood conditions concentrations mostly fall between 0,1% (1 000 p.p.m.) and 3% (30 000 p.p.m.) with the maximum concentration on record in southern Africa of 6,5%, measured at Jammersdrift on the Caledon River.

As will be shown in chapter 4, sediment concentrations and loads in rivers which carry fine sediments, are determined by the availability of sediments rather than the carrying capacity of the flows. It is thus understandable that the maximum concentration of 6,5% could have coincided with a discharge of only 80 $m^3/s$. A value of 6,5% is typical of maximum percentages which have been recorded in different parts of the world and it was not exceeded in the earlier South African records which have been lost.

### 2.3.4 Reservoir sediment surveys

Early reservoir basin resurveys which were performed to monitor sediment accumulation in existing reservoir basins were conducted in the dry as far as possible by means of standard tacheometrical survey procedures. Surveying below water was done by means of plumb lines connected to circular metal discs. The level at which the disc would come to rest in the soft upper sediment layers represented the sediment deposit surface. When echo-sounding equipment was introduced to do underwater surveys, problems were encountered in defining sediment surface levels. In order to make old and new surveys directly comparable the new apparatus was calibrated according to the depths provided by the old discs.

Until recently surveys were only conducted up to the full supply levels of reservoirs. As a significant proportion of the total sediment deposit typically lies above the full supply level the recorded sediment volume below the full supply level does not represent the total deposit and the difference is often between 10 and 20%.

Plotting of the surveys and subsequent planimetering of areas for volumetric calculations used to be tedious tasks.

### 2.3.5 Later developments

Although bottle samples are still being taken mainly for water quality monitoring it has been accepted that suspended sediment sampling should be performed by pumping samples from appropriate sampling points in the stream. As will be seen in chapter 5, a reasonable data basis exists of sediment yields for the higher sediment yield areas of South Africa. It is unlikely therefore that extensive longterm stream sampling monitoring will be required in future. It would be of great value however to institute short term measuring programmes in order to determine the relative yields from different sub-catchments.

Electronic sedimentation scales and other modern equipment have come into place to simplify grain size analyses and concentration determinations for large numbers of samples. Laboratory processing of samples has therefore become less cumbersome.

Reservoir basins are being resurveyed on a regular basis by the Department of Water Affairs with modern depth sounding and positioning as well as recording instruments. Surveying as well as plotting and volumetric calculations are being done rapidly and efficiently. There is no doubt that the monitoring of sediment loads through re-surveys of reservoir basins has become the more efficient way of determining average sediment loads and yields. Density differences and trap efficiencies should obviously be taken into consideration. (Chapter 4.4)

# 3. SEDIMENT TRANSPORT THEORY

## 3.1 Introduction

It is not possible to deal with the interactive processes which are involved in the transportation of sediment by fluids without a proper understanding of fluid mechanics. Traditional text-books on hydraulics are based on the laws of conservation of

- mass (e.g. continuity equation)
- energy (e.g. Bernoulli equation)
- momentum (e.g. momentum - force equation)

Although these equations are generally adequate in the analysis of fluid flows, they offer limited insight into the sediment-transporting characteristics of streams. We have found that an additional law, the law of conservation of power provides us with a much clearer picture of sediment transporting processes including:

- parameters for erosion initiation for both cohesive and cohesionless materials
- suspended sediment transport with so-called bed load a special case
- channel deformation processes
- the interrelationship between flow resistance and sediment transport.

Sediment transport is inseverably linked to flow resistance. Therefore the development of an understanding of sediment transport must begin with an analysis of flow resistance.

Typical textbooks on open channel flows deal with the development of flow resistance more or less in a chronological way, starting with the semi-empirical classical work of Prandtl and Von Karman which was prompted by aeronautical interests, modified for pipe flows and eventually distorted to describe open channel flows. The approach which is followed here, based on the power approach, has been found to be much more logical and comprehensible.

The power approach is treated comprehensively here as it is not covered properly in existing textbooks. (Chapters 3.2 to 3.6 contain the fundamental theory and readers who are only interested in the more practical aspects can continue reading from Chapter 3.7.)

## 3.2 Flow resistance in terms of shear stresses

The retarding effect that limits the movement of one fluid element relative to another is traditionally represented by way of so-called shear stresses. They represent momentum exchange across the planes within which the shear stresses are deemed to exist and derive from the equivalency between forces and momentum exchange. Equilibrium shear stresses are uniquely defined in uniform one-dimensional open channel flows.

Consider uniform stationary flow of a homogeneous liquid in a channel with infinite width, small longitudinal slope s and depth of flow D. The average point velocity in the x-direction at a distance y from the bed is v, with the y-axis taken perpendicular to the bed and the x-axis along the bed.

As there is no acceleration, the forces acting on the element with height (D-y), length $\Delta x$ and unit width have to be in equilibrium. It is convenient (as is customary) to represent the resistance to movement being encountered by the element by a "shear force" ($\tau.\Delta x$), acting along the lower plane of the element.

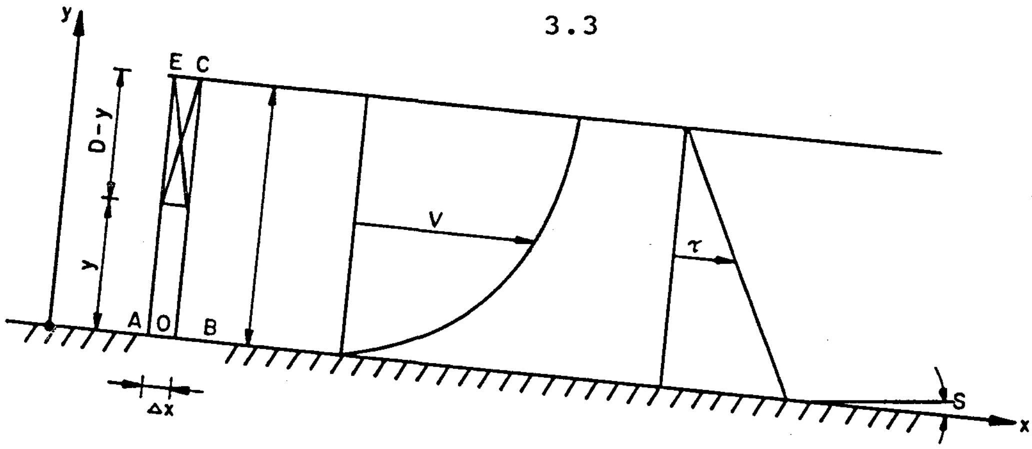



FIGURE 3.1

This opposing force must therefore be equal to the driving force which consists of the weight component of the element in the direction of flow, equal to $\rho g(D-y)\Delta x.\text{Sin } s \approx \rho g(D-y)\Delta x.s$, with $\rho$ the mass density of the liquid and g the acceleration due to gravity.

$$\therefore \quad \tau.\Delta x = \rho g(D-y)s.\Delta x$$
$$\text{or } \tau = \rho g(D-y)s \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.1)$$

The "shear stress" ($\tau$) therefore must increase linearly from zero at the surface to a maximum value of $\rho gsD$ at the bed, irrespective of the mechanisms by which it is generated.

Flow velocities next to the fixed boundary have to be zero - if this were not so, the point of action of the shear force would be transferred, which would only be possible if the boundary material were to be transported, resulting in work being done.

Mathematical description of velocity distribution is only possible if the relationship between shear stress ($\tau$) and velocity gradient ($\frac{dv}{dy}$) is known.

Wherever alternate modes of flow exist, that mode which requires the least applied power will prevail. The reason for this is that the mode which requires the least applied power represents the condition under which yield takes place most readily. Contrary to what may intuitively be assumed, this can result in a lower average velocity than in the alternative case.

### 3.3 Power balance in one-dimensional open channel flow

Consider the movement of a small fluid element with dimensions $\Delta x$, $\Delta y$ and unit width:

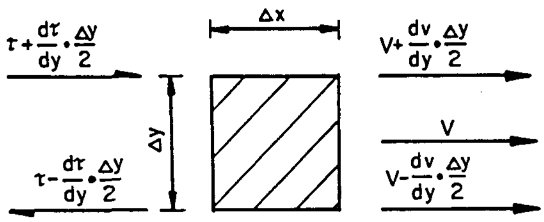



FIGURE 3.2

The velocity and shear stress vary across the element as shown. If the element translates with mean velocity v in a direction s relative to the horizontal, the power which is made available due to the steady rate of decrease in potential energy of the element equals

$$\rho g s \Delta x . \Delta y . v$$

The power deficit for the element equals the work done per unit time on the upper surface of the element minus the work done per unit time on the lower surface.

$$\therefore \text{ Power deficit } = (\tau + \frac{d\tau}{dy} \cdot \frac{\Delta y}{2})(v + \frac{dv}{dy} \cdot \frac{\Delta y}{2})\Delta x$$

$$- (\tau - \frac{d\tau}{dy} \cdot \frac{\Delta y}{2})(v - \frac{dv}{dy} \cdot \frac{\Delta y}{2})\Delta x$$

$$= (\tau \frac{dv}{dy} + v \frac{d\tau}{dy}) \Delta x . \Delta y$$

$$\therefore \quad \text{Power deficit per unit volume} = \tau \frac{dv}{dy} + v \frac{d\tau}{dy}$$

According to equation (3.1) $\tau = \rho g(D-y)s$

$$\therefore \quad \frac{d\tau}{dy} = -\rho gs$$

$$\therefore \quad \text{Power deficit per unit volume} = \tau \frac{dv}{dy} - \rho gsv$$

The term $\tau \frac{dv}{dy}$ represents the power applied per unit volume to deform the element or to maintain motion whereas the term $\rho gsv$ represents the amount of power made available by the element.

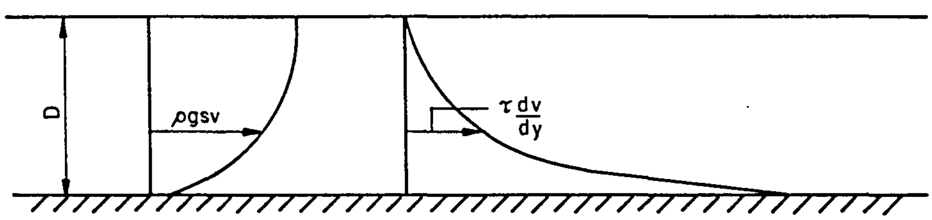



FIGURE 3.3

The variation of the functions $\tau \frac{dv}{dy}$ and $\rho gsv$ is shown diagrammatically in Figure 3.3 and it is evident that for the majority of flowing elements there is a considerable difference between the values of these functions.

In accordance with the principle of the conservation of power, the areas enclosed by the graphs should be equal.

$$\text{i.e.} \int_{y_o}^{D} \rho gsv\,dy = \int_{y_o}^{D} \tau \frac{dv}{dy}\,dy \quad \ldots\ldots\ldots\ldots\ldots \quad (3.2)$$

This equation proves to be valid for both laminar and turbulent flow, with $y_o$ = distance from the origin of the y-axis where the velocity is mathematically = 0.

**3.4 Velocity variation in laminar flow**

In the case of laminar flow, the shear stresses are generated by liquid interaction on a molecular scale and the relationship between shear stress and velocity gradient ($\frac{dv}{dy}$) is expressed through the well-known Newtonian equation:

$$\tau = \mu \frac{dv}{dy} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.3)$$

where $\mu$ = dynamic viscosity of the liquid which at a given temperature is a unique measure of the molecular interaction of the liquid.

Values in equations (3.1) and (3.3) can be equated and the velocity at a distance y from the bed is found to be

$$v = \frac{\rho gs}{2\mu} [\ 2Dy - y^2] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.4)$$

**3.5 Velocity variation in fully developed turbulent flow**

In the case of turbulent flow, the apparent shear stresses are generated by eddying motion on a large scale as opposed to movement on a molecular scale in laminar flow. Portions of the fluid temporarily move as units in the form of eddies, or parts of such eddies which instantaneously follow circular paths. From continuity considerations, the angular velocity of an eddy must equal the velocity gradient $\frac{dv}{dy}$ which exists at the centre of the eddy.

Consider a cylindrical element of an eddy with outer radius R which momentarily exists with its centre in a plane 0-0 where the apparent shear stress has to be $\tau$.

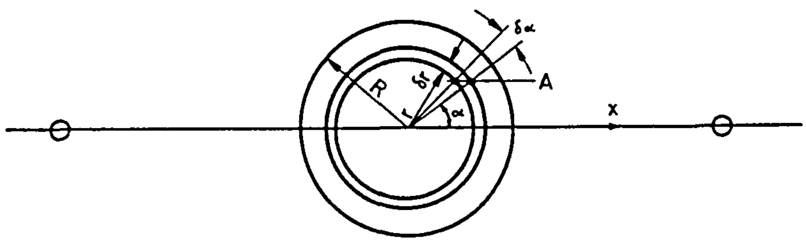



FIGURE 3.4

According to Newton's second law, the resisting force in the x-direction equals the rate of exchange of x-momentum with time.

For an area element $\delta A$ parallel to the 0-0 plane, at a distance r from the centre, the shear force equals $\tau.\delta A$ which has to be equal to the rate of x-momentum exchange across the area

$$\therefore \quad \tau.\delta A = \rho(r\frac{dv}{dy} . \text{Cos } \alpha)\delta A(r\frac{dv}{dy} . \text{Sin } \alpha)$$

$$\therefore \quad \tau = \rho r^2 (\frac{dv}{dy})^2 \ \text{Sin } \alpha \text{ Cos } \alpha$$

The average value of the shear stress across the cylindrical element therefore equals:

$$\bar{\tau} = \frac{4\int_0^R \int_0^{\pi/2} \rho \left(\frac{dv}{dy}\right)^2 r^3 \ \mathrm{Cos}\ \alpha \ \mathrm{Sin}\ \alpha \ dr d\alpha}{\pi R^2}$$

$$= \frac{\rho}{2\pi} R^2 \left(\frac{dv}{dy}\right)^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.5)$$

$$= (0{,}3989)^2 \rho R^2 \left(\frac{dv}{dy}\right)^2$$

$$\approx (0{,}4)^2 \rho R^2 \left(\frac{dv}{dy}\right)^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.6)$$

This formula is equivalent to the well-known Prandtl equation for turbulent shear stress

$$\tau = \rho \ell^2 \left(\frac{dv}{dy}\right)^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.7)$$

in which $\ell$ = mixing length.

In comparing equations (3.6) and (3.7) the following remark by Prandtl (1952) concerning mixing length is of interest:

"Clearly, it is essential to have a length which may be interpreted as the diameter of the balls of fluid which move as a whole and also as the path transversed by these balls relative to the rest of the fluid before they lose their individuality again by mixing with the turbulent fluid by which they are surrounded."

The interpretation that the mixing length and the diameter of the spheres are related is apparent from the foregoing.

The factor $\frac{1}{2\pi^2}$ in equation (3.5), which is very nearly equal to $(0,4)^2$, represents $(\kappa)^2$ where $\kappa$ is the so-called von Karman coefficient, the value of which has experimentally been found to be equal 0,4 for homogeneous fluids. This factor compensates for the fact that the momentum exchange varies across the cylindrical element.

From equations (3.1) and (3.5) it follows that

$$\rho g s\ (D-y) = \frac{\rho}{2\pi} R^2 \left(\frac{dv}{dy}\right)^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.8)$$

To be able to derive the velocity distribution equation, it is necessary to determine how R varies as a function of y.

In the case of turbulent flow, layers of fluid cannot "slip" relative to each other due to the eddying motion of the fluid.

A thin element ABCE (Figure 3.1) of a stream therefore momentarily has to move as a unit. The velocity at 0 next to the boundary, has to be equal to zero, and the only possible way in which ABCE can momentarily move as a unit, is by relative rotation around 0. As the fluid flow in the channel is translatory, such rotational movement is not possible unless it is accompanied by translation of the centre of rotation 0. A small fluid element at a distance y from the bed rotates with angular velocity $\frac{dv}{dy}$ and the translatory velocity relative to the centre of rotation is $y\frac{dv}{dy}$. Translatory flow in the channel will only be possible if the centre of rotation translates with a speed of $y\frac{dv}{dy}$ and because the centre of rotation is common to all elements in the vertical

$$y\frac{dv}{dy} = \text{Constant}$$

$$= V_o, \text{ the velocity of the centre of rotation}$$

From equation (3.8) $\frac{dv}{dy} = \frac{\sqrt{2\pi gs(D-y)}}{R}$

$$\text{and } V_o = y\frac{dv}{dy} = \frac{y\sqrt{2\pi gs(D-y)}}{R} \quad \ldots\ldots \quad (3.9)$$

When y approaches zero, $D-y \approx D$ and y can be equated to $R_o$, where $R_o$ is the radius of eddies next to the bed.

$$\therefore \quad V_o = y\frac{dv}{dy} = \sqrt{2\pi gDs} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3.10)$$

($\sqrt{gDs}$ is often called the shear velocity though no physical meaning is attached to it).

According to equations (3.8) and (3.10), the equation for R is:

$$R = y\sqrt{\frac{D-y}{D}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.11)$$

and equation (3.9) becomes

$$\frac{dv}{dy} = \frac{\sqrt{2\pi gDs}}{y} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.12)$$

Integration of equation (3.12) leads to

$$v = \sqrt{2\pi gDs} \,.\, \ln{}^{y}/_{y_o} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.13)$$

where $y_o$ is the ordinate of the level at which the velocity is mathematically = 0. For the simple case where the irregularities on the bed consist of identical halfspheres, stacked closely together, with radii $R_o$, it is possible to determine the value of $y_o$ theoretically. To fit in with the geometry of the boundary, it is evident that the eddies which are formed right next to the boundary, will have practically the same diameter as the irregularities and that these eddies will be approximately spherical in shape. Equation (3.5) was derived for a cylindrical element with radius R. Across a sphere, the outer radius varies along the centre line of the sphere with the radius $R_z$ at a distance z from the centre being given by the equation.

$$R_z{}^2 = R^2 - z^2$$

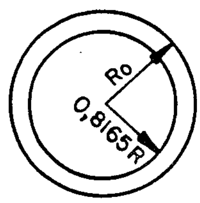



FIGURE 3.5

The effective radius $R_{eff}$ of a sphere in terms of the outer radius R, is therefore given by:

$$R^2{}_{eff} = \int_o^R \frac{(R^2 - z^2)dz}{R} = \frac{2}{3} R^2$$

However $R = y.\sqrt{\frac{D-y}{D}}$ ............................ (3.11)

Near the bed R mathematically = y and y = $R_o$ may be taken to represent the ordinate of the centre of the boundary eddies. Because of the fact that the spaces between the undersides of the eddies are filled by the solid irregularities on the bed, the effective radius of these eddies is given by:

$$R_{eff} = \sqrt{\frac{2}{3}}\, R_o$$

$$= 0{,}8165\ R_o$$

The effective flow boundary is therefore situated at a distance 0,1835 $R_o$ from the mathematical flow boundary, and the translatory velocity here must equal $V_o$. Thus $V_o$ = v and from (3.10) and (3.13).

$$\sqrt{2\pi gDs} = \sqrt{2\pi gDs}\ \ln{}^{y}/y_o$$

$$\therefore \ln\left(\frac{0{,}1835.R_o}{y_o}\right) = 1$$

$$\therefore y_o = \frac{0{,}1835\ R_o}{e}$$

$$\therefore y_o = \frac{R_o}{14{,}8} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.14)$$

with e = natural logarithm base.

Equation (3.13) can now be integrated to give the average velocity ($\bar{v}$)

$$\therefore \bar{v} = \sqrt{2\pi gDs}\ \ln\frac{D}{ey_o} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.15)$$

$$\therefore \bar{v} = \sqrt{2\pi gDs}\ \ln\frac{5{,}45D}{R_o}$$

$$\text{or} \quad \bar{v} = 5{,}77\sqrt{gDs}\ \log\frac{5{,}45D}{R_o} \quad \ldots\ldots\ldots\ldots\ldots \quad (3.16)$$

This formula compares well with semi-empirical relationships e.g. that of the Committee on Hydromechanics (1963) for a wide channel, written in a comparable form:

$$\overline{v} = 5.75\sqrt{gDs}\ \log \frac{5.55D}{R_o}$$

## 3.6 Transition from laminar to turbulent flow

**Flow over a smooth bed**

In order to understand why flow will be either laminar or turbulent, it is necessary to consider the case of flow over a smooth bed:

It was shown in section 3.5 that for fully developed turbulent flow, the velocity distribution is given by the equation

$$v = \sqrt{2\pi gDs}\ \ln{}^{y}/y_o = \sqrt{2\pi gDs}\ \ln \frac{14{,}8y}{R_o}$$

(equations 3.13 and 3.14)

where $R_o$ represents the radius of eddies formed against the bed.

It is evident from equation (3.2) that $(\tau\frac{dv}{dy})_o$ i.e. the power which is applied per unit volume to maintain motion next to the boundary, represents the maximum value of the function $(\tau\frac{dv}{dy})$ through the vertical section.

In the case of turbulent flow past a "smooth" boundary, that is a boundary where the formation of eddies with extremely small radii would fit in with the dimensions of the excrescences on the bed, the value of

$$\left(\frac{dv}{dy}\right) = \frac{\sqrt{2\pi gDs}}{y_o}$$

would become extremely high, because $y_o$ is proportional to the radius of these eddies.

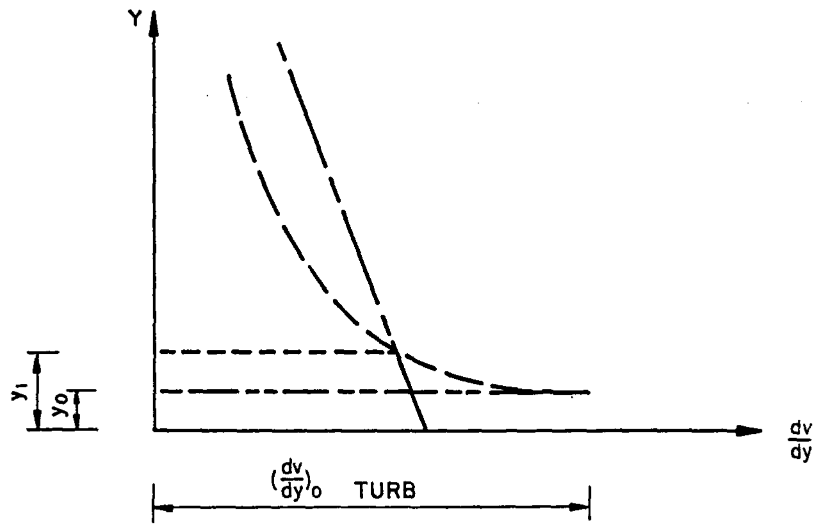



FIGURE 3.6

In accordance with the concept of least applied power, flow near a boundary will be either turbulent or laminar, depending upon which type of flow requires the smaller amount of power per unit volume $(\tau\frac{dv}{dy})$ to maintain it.

For a given value of the shear stress against the boundary $\tau_o$, flow will start to change from laminar to turbulent where

$$\left(\frac{dv}{dy}\right)_{o\ \text{Turbulent}} = \left(\frac{dv}{dy}\right)_{o\ \text{Laminar}}$$

$$\therefore \frac{dv}{dy} = \frac{\sqrt{2\pi gDs}}{y_1} = \rho gs\,\frac{(D-y_1)}{\mu} \approx \frac{\rho gsD}{\mu} \quad \ldots\ldots\ldots \quad (3.17)$$

$$\therefore\ y_1 = \frac{\sqrt{2\pi\nu}}{\sqrt{gDs}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.18)$$

At this level, the velocity according to equation (3.4) for laminar flow, would be

$$= \frac{\rho gs}{\mu}.Dy_1$$

$$= \sqrt{2\pi gDs} = \{\text{required translatory velocity of the centre of rotation for turbulent flow.}\}$$

It therefore follows that a thin layer of laminar flow against a "smooth" boundary creates the necessary moving platform relative to which the necessary condition for turbulent flow $y\frac{dv}{dy}$ = Constant, can be satisfied.

With $y_1 \ll D$ the value of the shear stress along the transition zone will be $\rho gsD$. This value can be expressed in terms of the equation for turbulent shear stress:

$$\tau = \rho gsD = \frac{\rho}{2\pi} \cdot R_o^2 \left(\frac{dv}{dy}\right)^2 \quad \ldots\ldots\ldots\ldots\ldots \quad (3.5)$$

with $\frac{dv}{dy} = \frac{\rho gsD}{\mu}$ from Equation (3.3)

The radii of eddies in the transition zone therefore will be

$$= \frac{\sqrt{2\pi\nu}}{\sqrt{gsD}}$$

According to equation (3.16) the average velocity v as a function of the radius of the boundary eddies, is expressed as

$$\bar{v} = 5{,}77\sqrt{gDs}\ \log \frac{5{,}45D}{R_o} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.19)$$

and therefore it follows that

$$v = 5{,}77\sqrt{gDs}\ \log \frac{2{,}17\ D\sqrt{gDs}}{\upsilon} \quad \ldots\ldots\ldots\ldots\ldots \quad (3.10)$$

Experimental results such as those given by the Committee on Hydromechanics (1963) correspond with this result except for the fact that most experimentalists have obtained values varying between 2,6 and 3,7 instead of 2,17 for the second coefficient, and 5,75 instead of 5,77 for the first coefficient.

As the value of v is relatively insensitive to variation in the value of the second coefficient the agreement is reasonable and the differences are possibly due to transition phenomena not allowed for in the theory.

**Critical Reynolds Numbers**

From the foregoing it is evident that in the case of flow for which $\sqrt{2\pi gDs}$ is large, transition from laminar to turbulent flow will take place very near to the physical boundary. Such cases of flow will generally be characterized by high Reynolds Numbers. ($R_e = \frac{\bar{v}D}{\nu}$). For decreasing values of $\sqrt{2\pi gDs}$ and corresponding decreases in the value of $R_e$, the thickness of the laminar flow zone will increase, and for very low values of the $R_e$ Number, flow will be wholly laminar.

If the relationships between the friction factor (e.g. f in the Darcy-Weisbach equation), and Reynolds Number are known, the value of the lower critical Reynolds Number can be determined theoretically. The value of the lower critical Reynolds Number i.e. that $R_e$ value at which flow begins to change from wholly laminar to turbulent, is found to be a function of the corresponding friction coefficients for turbulent flow (Rooseboom, 1974).

## 3.7 Interaction between flowing fluid and transportable material

### Incipient bed movement conditions

One of the most fundamental concepts in sediment transport theory is the critical threshold condition where the transporting capacity of a stream becomes sufficient to begin moving sediment along its bed.

The classical and best known criteria depicting the boundary between flow conditions under which cohesionless bed material will be transported and those under which such material will not be transported are the Hjulstrom and Shields diagrams (Hjulstrom, 1935) (Shields, 1936).

Hjulstrom's diagram simply relates critical velocity to particle diameter and does not provide an accurate criterion. The Shields diagram was developed on the basis of dimensional analysis of certain variables involved in sediment transport. Primary variables in the Shields analysis are bed shear stress, particle diameter, particle density, fluid density and fluid viscosity.

Its main shortcoming is that particle grain size is neither a truly representative nor a unique measure of transportability. In certain practical situations e.g. where artificial armouring units are present, particle size becomes a meaningless concept. The settling velocity of particles is a more significant measure in the case of non-cohesive material, while cohesive forces play a determining role in the entrainment of cohesive materials.

The power approach provides us with the ability to define both the transporting capacity of a stream and the effort required to transport material in directly comparable terms.

It has been argued that whenever alternative modes of flow exist, that mode which requires the least amount of unit power will be followed. Accordingly it can be argued that fluid flowing over movable material would not transport such material unless this would result in a decrease in the amount of unit power which is being applied. Alternatively if two modes of structural yielding exists yielding will take place according to that mode which offers the least resistance.

Where flow takes place over movable material and the relatively large amount of unit power required to maintain motion along the bed becomes greater than that which would be required in the process of deformation of the bed, the stream should begin to transport the bed material rather than persist in its existing mode of flow. The applied power required per unit volume to suspend a particle with density $\rho_s$ and settling velocity $V_{ss}$ in a fluid with density $\rho$ equals $(\rho_s-\rho)\ g\ V_{ss}$.

In rough turbulent flow (section 3.5) the unit stream power applied in maintaining motion along a bed consisting of particles with diameter d ($\approx 2R_o$) is proportional to

$$\frac{\rho g s D\sqrt{gDs}}{d}$$

In terms of the concept of minimum applied power, the stream will begin to entrain particles when the power required to suspend the particles becomes less that the power required to maintain the status quo.

At that stage

$$(\rho_s - \rho)\ g\ V_{ss} \propto \rho g s D \frac{\sqrt{gDs}}{d} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.20)$$

According to the general equation for settling velocity (Graf, 1971)

$$V_{ss} \propto \sqrt{\frac{(\rho_s - \rho)\, gd}{\rho\ C_d}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.21)$$

Assuming that $C_d$, the drag coefficient, is a constant, which is true for larger diameters, then from (3.20) and (3.21) the condition of incipient sediment motion under rough turbulent flow conditions is depicted by

$$\frac{\sqrt{gDs}}{V_{ss}} = \text{constant} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.22)$$

As can be seen in Figure 3.7, this relationship fits measured data as compiled by Yang (1973) very well, with the value of the constant = 0,12, for values of

$$\frac{\sqrt{gDs}}{\upsilon}.d \;>\; 13$$

Similarly, in smooth turbulent flow as well as in completely laminar flow the unit applied stream power equals.

$$\frac{(\rho g s D)^2}{\rho \upsilon}$$

The corresponding equation for settling velocity (Graf, 1971) under viscous conditions states that

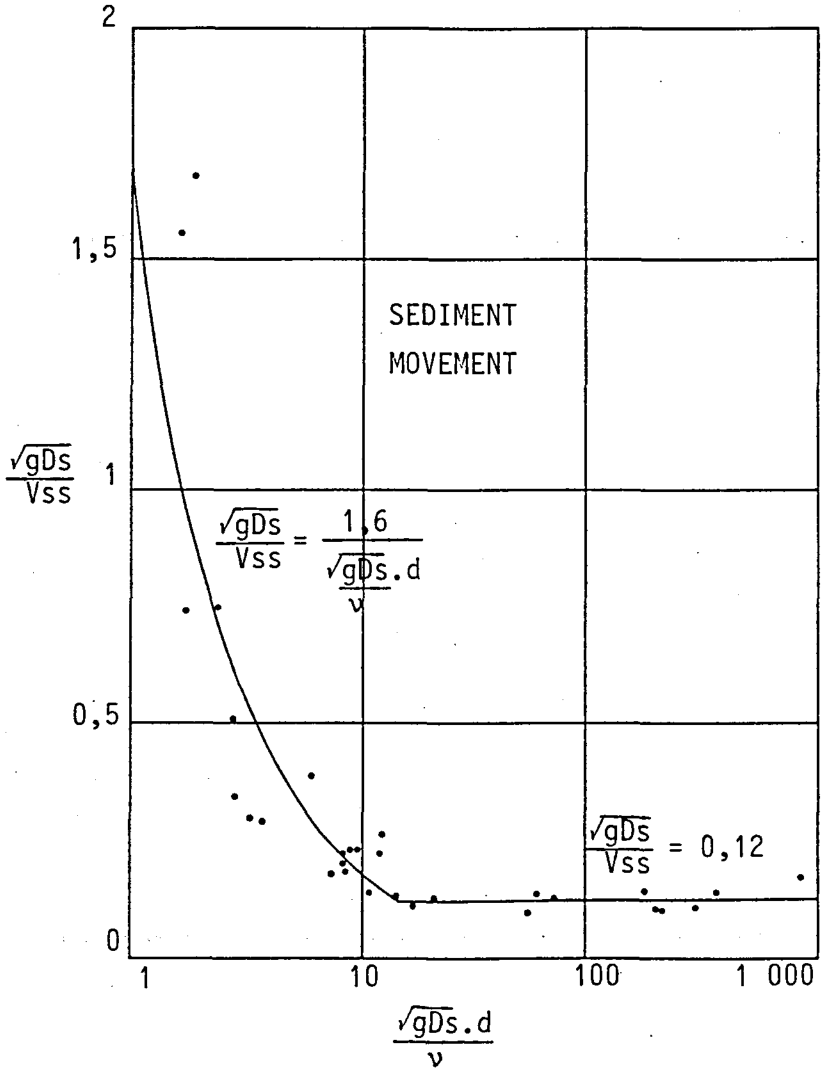



FIGURE 3.7
CRITICAL CONDITIONS FOR
COHESIONLESS SEDIMENT PARTICLES

$$V_{ss} \propto d^2 g \frac{(\rho_s - \rho)}{\rho \nu} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.23)$$

Accordingly, the relationship for values of $\frac{\sqrt{gDs}\ d}{\nu} < 13$ calibrated with data by Grass (1970) and Yang (1973) is found to be

$$\frac{\sqrt{gDs}}{V_{ss}} = \frac{1,6}{\frac{\sqrt{gDs}}{\nu} \cdot d}$$

In the case of cohesive soils neither particle size nor settling velocity represents erodability. By comparing the power applied by an eroding stream to the power required to dislodge cohesive particles Rooseboom and Mülke (1982) have developed a system through which initiation of severe erosion along a steep slope can be forecast (Figure 3.8).

For this purpose it is necessary to measure the power required to dislodge particles of a given soil in a standard shear box test. (Farnell SM8 with shear box size 61,5 x 61,5 mm, loading 52,4 kg and speed 1,2 mm/s). With the velocity of the shear box kept constant, this power is represented by F, the mean shearing force. For a given slope (1/z), absolute surface roughness (k), and rainfall intensity known, the distance down the slope (L) at which severe erosion will begin can be determined from Figure 3.8.

### 3.8 Suspended sediment concentration variation across a stream section

A general equation which describes suspended sediment concentration variation in the y-direction (perpendicular to the bed) in one dimensional stationary turbulent open-channel flow, can be derived as follows:

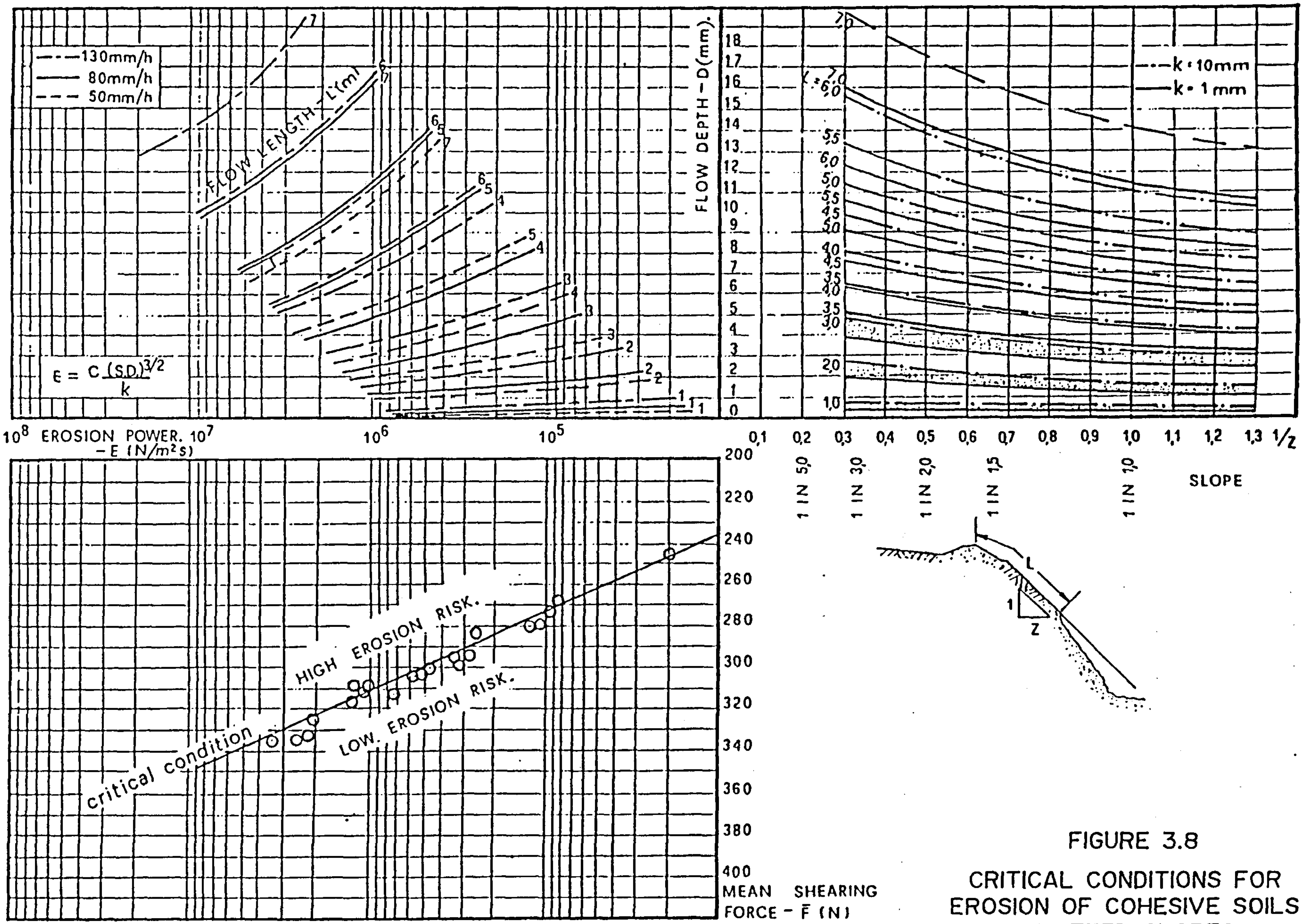



FIGURE 3.8

CRITICAL CONDITIONS FOR EROSION OF COHESIVE SOILS ON STEEP SLOPES

Consider a cylindrical eddy element with radius R and unit width which rotates with angular velodity $\frac{dv}{dy}$, equal to the velocity gradient across the element.

The average sediment concentration in a "horizontal" plane through the eddy centre is C, and the concentration gradient "vertically" across the element equals $\frac{dC}{dy}$.

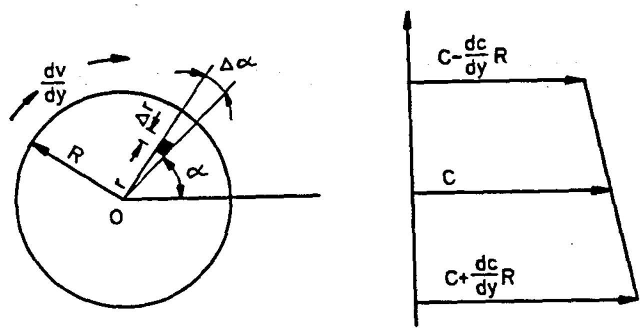



FIGURE 3.9

An element within the cylinder with area $\Delta A = \Delta r . r . \Delta\alpha$ rotates with constant angular velocity $\frac{dv}{dy}$ and radius r. As it moves downwards, the sediment concentration within the element is increased whereas during its upward journey, the concentration decreases. The amount of power (P) which is necessary to change the sediment concentration of the element at any stage, is equal to the rate of change of the kinetic energy of the element with time.

$$\therefore P = \frac{d}{dt} \left[ \tfrac{1}{2} I \left(\frac{dv}{dy}\right)^2 \right]$$

with I = moment of inertia of the element around O

$= mr^2$ with m = mass of the small element and

r = distance from the centre

$$\therefore P = \left(\frac{dv}{dy}\right)^2 \frac{r^2}{2} \cdot \frac{dm}{dt}$$

$m = \rho.\Delta A + (\rho_S - \rho)C.\Delta A$, with

$\rho_S$ = mass density of the sediment and
$\rho$ = mass density of the fluid

$$\therefore \frac{dm}{dt} = (\rho_S-\rho)\frac{dC}{dt}.\Delta A = (\rho_S-\rho)\frac{dC}{dy} \cdot \frac{dy}{dt} \cdot \Delta A$$

From Figure 3.9

$$\frac{dy}{dt} = \frac{d}{dt} (r \text{ Sin } \alpha)$$

$$= r(\text{Cos } \alpha)\frac{d\alpha}{dt}$$

$$= r\left(\frac{dv}{dy}\right) \text{Cos } \alpha$$

(Because $\frac{d\alpha}{dt}$ = angular velocity = $\frac{dv}{dy}$)

$$\therefore P = \left(\frac{dv}{dy}\right)^2 \frac{r^2}{2} (\rho_S-\rho)\frac{dC}{dy} \cdot r(\text{Cos } \alpha)\frac{dv}{dy} \cdot rdrd\alpha$$

To find the average value of the power (P) integrate across the full area and divide the result by the total area:

$$\therefore \quad \overline{P} = \frac{4 \times \frac{1}{2} \int_0^{\pi/2} \int_0^R \left(\frac{dv}{dy}\right)^3 r^4 \; (\rho_S-\rho)\frac{dC}{dy} \text{ Cos } \alpha \; dr.d\alpha}{\pi R^2}$$

$$= \frac{\left(\frac{dv}{dy}\right)^3 (\rho_s-\rho)\, 4R^5 \frac{dC}{dy}}{10\pi R^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3.24)$$

According to section 3.2.4, the average value of the shear stress across an eddy element with radius R in a homogeneous fluid equals:

$$\tau = \frac{\rho}{2\pi} R^2 \left(\frac{dv}{dy}\right)^2$$

If it is assumed that his expression is also valid in the case of flow with suspended sediment, substitution into equation (3.24) leads to

$$\overline{P} = \frac{4}{5}\tau\frac{dv}{dy}\,\frac{(\rho_s-\rho)}{\rho}\,\frac{dC}{dy}\,.\,R \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3.25)$$

Another expression for the average amount of power which has to be applied to maintain the steady state of sediment suspension, can be derived as follows:

An element with area $\Delta A$ takes a time of $\frac{2\pi}{dv/dy}$ for one complete revolution. If the suspended particles all have a settling velocity of $v_{ss}$, they would have settled a distance $\frac{2\pi(V_{22})}{dv/dy}$ during one revolution if work was not done to keep them in suspension.

The suspension is maintained through centrifugal acceleration of the sediment particles, the accelerative force on an element with area $\Delta A$ being equal to $(\rho_s-\rho)C.r(\frac{dv}{dy})^2$ dA.

Therefore with an average concentration value of $\overline{C}$, the average amount of power ($\overline{P}$) which is necessary to maintain the suspension, is given by

$$\bar{P} = \frac{\int_0^A (\rho_s-\rho)\bar{C}r\left(\frac{dv}{dy}\right)^2 v_{ss} dA}{\pi R^2}$$

$$= \frac{\int_0^R (\rho_s-\rho)\bar{C}r\left(\frac{dv}{dy}\right)^2 v_{ss}.2\pi r.dr}{\pi R^2}$$

$$= \frac{2}{3}(\rho_s-\rho)v_{ss}\left(\frac{dv}{dy}\right)^2 \bar{C}.R \quad \ldots\ldots\ldots\ldots \quad (3.26)$$

from equations (25) and (26) it follows:

$$\therefore \frac{4}{5}\frac{dv}{dy}\left(\frac{\rho_s-\rho}{\rho}\right)\frac{dC}{dy} R = \frac{2}{3}(\rho_s-\rho)v_{ss}\left(\frac{dv}{dy}\right)^2 \bar{C}.R$$

and because $\tau = \rho gs(D - y)$ and $\frac{dv}{dy} = \frac{\sqrt{2\pi gDs}}{y}$

$$\therefore \frac{dC}{C} = \frac{10}{12}\frac{\sqrt{2\pi}v_{ss}}{\sqrt{gDs}} \cdot \frac{D\,dy}{y(D - y)} \quad \ldots\ldots\ldots\ldots \quad (3.27)$$

This equation is identical to the classical differential equation derived by Rouse (1937) by means of diffusion theory except for the factor $\frac{10}{12}$ which occurs in equation (3.27).

The term $\frac{\sqrt{2\pi}v_{ss}}{\sqrt{gDs}}$ is often denoted by Z in literature. If $\frac{10\sqrt{2\pi}v_{ss}}{12\sqrt{gDs}}$ is denoted by $Z_1$, it follows that

$$Z_1 = 0{,}833\ Z \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.28)$$

The integrated solution of equation (3.27) is of course similar to that of the Rouse equation with $Z_1$, instead of Z:

$$\frac{C}{C_a} = \left(\frac{D - y}{y} \cdot \frac{a}{D - a}\right)^{Z_1} \quad \ldots\ldots\ldots\ldots\ldots \quad (3.29)$$

where $C_a$ is the reference concentration at a distance a from the bed. (See Figure 3.9).

Chien (1954) published results of measured values of $Z_1$, as compared to values of Z. The equation $Z_1 = 0.833$ Z fits the data much better than the relationship $Z_1 = Z$ which should exist according to the diffusion theory (See Figure 3.10).

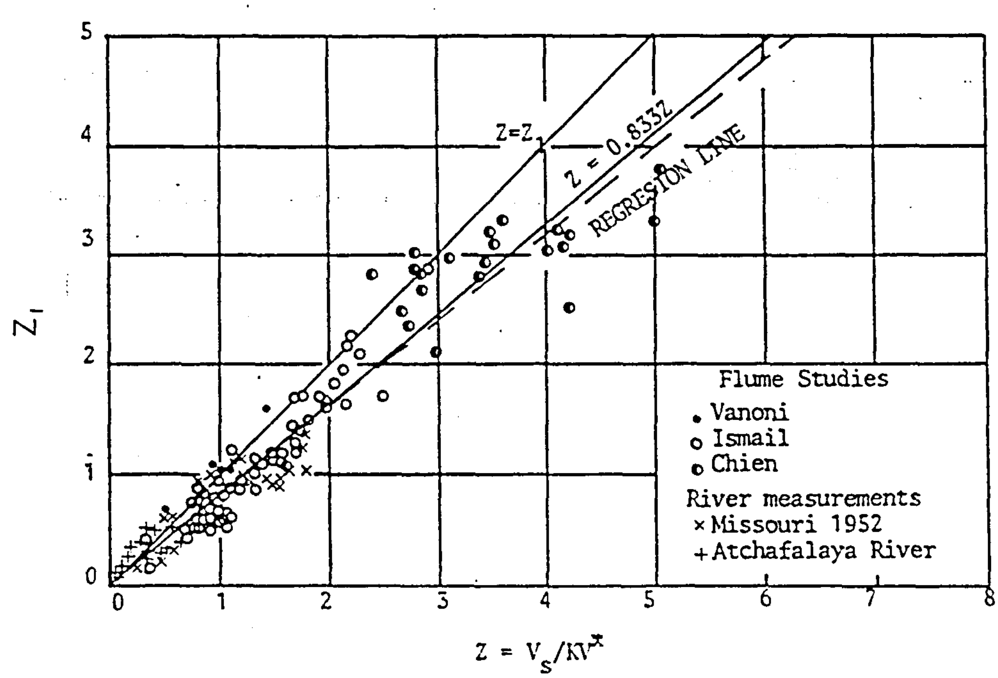



FIGURE 3.10

Equation (3.29) is equivalent to

$$\frac{C}{C_a} = \frac{\left(\tau \frac{dv}{dy}\right)^{Z_1}}{\left(\tau \frac{dv}{dy}\right)_a^{Z_1}}$$

i.e. the concentration at any level is proportional to the (applied power)$^{Z_1}$, with the limiting maximum value corresponding to a value of $y = y_o$. This relationship may be used to determine the total sediment load.

## 3.9 Total sediment loads

### 3.9.1 Suspended transport

According to equation (3.29) the relative sediment concentration at a distance y above the bed in a stream with depth D is $\propto \left(\frac{D-y}{y}\right)^Z$

with $Z \propto \dfrac{V_{ss}}{\sqrt{gDS}}$.

In cases where Z values are low i.e. where the settling velocity of the (small) particles being carried is small compared to the velocity of the stream, the sediment concentration varies very little with depth and a homogeneous suspension is obtained. On the other hand if the transporting capacity just exceeds the critical condition e.g. $\frac{\sqrt{gDS}}{V_{ss}}$ slightly > 0,12 (Figure 3.7) for turbulent boundary conditions then the sediment particles will be carried close to the bed and a ceiling will exist above which the applied stream power will be too low to lift particles with a given settling velocity. The latter condition is often referred to as bed load transport i.e. transport that takes place only along the bed.

### 3.9.2 Bed load transport

Early investigators who were mainly familiar with certain European rivers in which little sediment is carried in a fully suspended state, developed empirical formulae (types a and b, equations 3.31 and 3.32) in attempts to relate transporting capacity to flow conditions. Later contributions mainly by H A Einstein, were derived through sophisticated statistical analyses. To distinguish these formulae from other formulae for suspended and total loads, these formulae are called bed load formulae. The different bed load formulae are often similar and can be divided into groups of the same type (Graf 1971).

(a) Du Boys type equations

$$q_s = \alpha\tau_o(\tau_o - \tau_{cr}) \quad \text{.................} \quad (3.31)$$

with $q_s$ = sediment discharge per unit width

$\tau_o$ = acting bed shear stress

$\tau_{cr}$ = critical bed shear stress

$\alpha$ = empirical coefficient

(b) Schoklitsch-type equations

$$q_s = \alpha s^{\beta} (q - q_{cr}) \quad \text{................} \quad (3.32)$$

$\alpha$ and $\beta$ = empirical coefficients

$s$ = energy slope

$q$ = discharge per unit width

(c) Einstein-type equations

$$q_s = \frac{\rho_s \cdot g\, d^2\, k_1\, k_2}{k_3\, k_4} \; \frac{g(\rho_s - \rho)}{d.\rho} \quad \text{.....} \quad (3.33)$$

with $\rho_s$ = mass density of sediment

$d$ = particle diameter

$k_1$, $k_2$, $k_3$ and $k_4$ empirical coefficients which compensate for assumptions made.

Various factors complicate practical application of these formulae:

(i) Limited validity of empirical coefficients
(ii) Availability of transportable material
(iii) Self-changing transporting capacity of a stream through deformation of the bed profile.

**3.9.3 Total load**

An increasing number of sediment transport specialists believe that the differentiation between suspended load and bed load is artificial and unnecessary. It may be argued that the one type of load is a special case of the other, and that it should be possible to have a single formula which represents the total carrying capacity of a stream. The case of suspended sediment transport with a relatively large Z value is equivalent to the bed load condition. As it is also possible to establish the incipient motion criteria by means of suspension theory (chapter 3.2.6), the suspension theories effectively cover the full range of transport phases. They therefore are well suited to the analysis of total carrying capacity.

In terms of the principle of conservation of power, the average amount of power applied must be equal to the average amount of power which becomes available. This enables us to express transporting capacity in terms of flow parameters:

$$q_s = \int_{Y_o}^{D} C\ v\ dy \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.34)$$

$$\text{with } C \propto \left(\tau\frac{dv}{dy}\right)^{z} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.30)$$

leading to an equation of the form: (Rooseboom, 1975)

$$\log \frac{q_s}{q} = \alpha \log \overline{v}s + \beta \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.35)$$

Yang (1972) found through statistical analyses of available data that equation (3.35) describes sediment transporting capacity particularly well. It may be concluded that this type of equation forms the best basis for calculation of the maximum sediment transport capacity of a stream. This formula has been calibrated for the limiting conditions which exist within reservoirs where the transporting capacity determines the sediment load with the excess load being deposited. (Figure 3.11) (Rooseboom & Van Vuuren, 1988)

### 3.10 Sediment transporting mechanisms in reservoirs

Three main mechanisms are involved in sediment transport within reservoirs viz turbulent suspension, density currents and colloidal suspension. Turbulent suspension as described in chapter 3.8 plays the dominant role in the transportation of sediment within reservoirs.

With turbulent suspension, the concentration variation can be described by the equation

$$\frac{C}{C_a} = \left(\frac{D-y}{y} \cdot \frac{a}{D-a}\right)^{z_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.29)$$

with $C$ = sediment concentration at a distance $y$ above the bed

$C_a$ = sediment concentration at the reference level a distance $a$ above the bed

$D$ = total flow depth

and $z \propto \dfrac{V_{ss}}{\sqrt{gDs}}$

with $V_{ss}$ = particle settling velocity
$s$ = energy slope

The following limiting turbulent transporting phases can be identified in reservoirs:
When the suspended sediment particles are small relative to the transporting capacity of the stream

$$\left(\frac{V_{ss}}{\sqrt{gDs}} \dashrightarrow 0\right)$$

sediment concentrations will vary little across sections and nearly homogeneous suspensions are obtained. Examples of suspended sediment concentration variations through a reservoir are contained in Figure 3.11. The positions of the sections are indicated in Figure 3.12. It is evident that even with high discharges passing through the reservoir very little sediment reaches the lower parts of the reservoir. This results from the fact that in terms of equation 3.35, the limiting concentration which can be carried in suspension is a function of the (flow velocity)$^3$. Thus as reservoirs become deeper and wider, the average velocity drops rapidly and the carrying capacity becomes the limiting factor in determining the load. As can be seen in the lower diagram (Figure 3.12) the sediment load decreases rapidly in the downstream direction with the excess load being deposited to form a delta. The singular relationship which exists between sediment load and transporting capacity under these conditions is depicted in Figure 3.13.

In cases where transported particles are very large relative to the carrying capacity of the stream, i.e.

$$\left(\frac{V_{ss}}{\sqrt{gDs}} \dashrightarrow 8{,}3\right)$$

sediment concentrations along the bed become much higher than near the surface and in the extreme case sediment particles are transported only along the bed. Once the critical condition is exceeded, i.e.

$$\left(\frac{V_{ss}}{\sqrt{gDs}} > 8,3\right)$$

movement of sediment through turbulent suspension ceases.

Turbulent suspension with large concentration differences is characterized by

$$\left(\frac{V_{ss}}{\sqrt{gDs}} \dashrightarrow 8,3\right)$$

and should not be confused with density currents.

**Density currents**

Density currents develop where a layer of fluid moves in beneath a layer of lower density. The sharp discontinuity which exists between the upper and lower fluids is characteristic of true density currents. A classical example of concentration variations associated with a sediment induced current, observed in Lade Mead on September 3rd 1940: (Howard, 1953)

| Level | Sediment Concentration |
|---|---|
| ± 317 m (water surface) | - |
| 214,27 | 0,14% |
| 214,12 | 21,3% |
| 213,96 | 27,0% |
| 213,05 | 28,2% |
| ± 190 m (bed) | - |

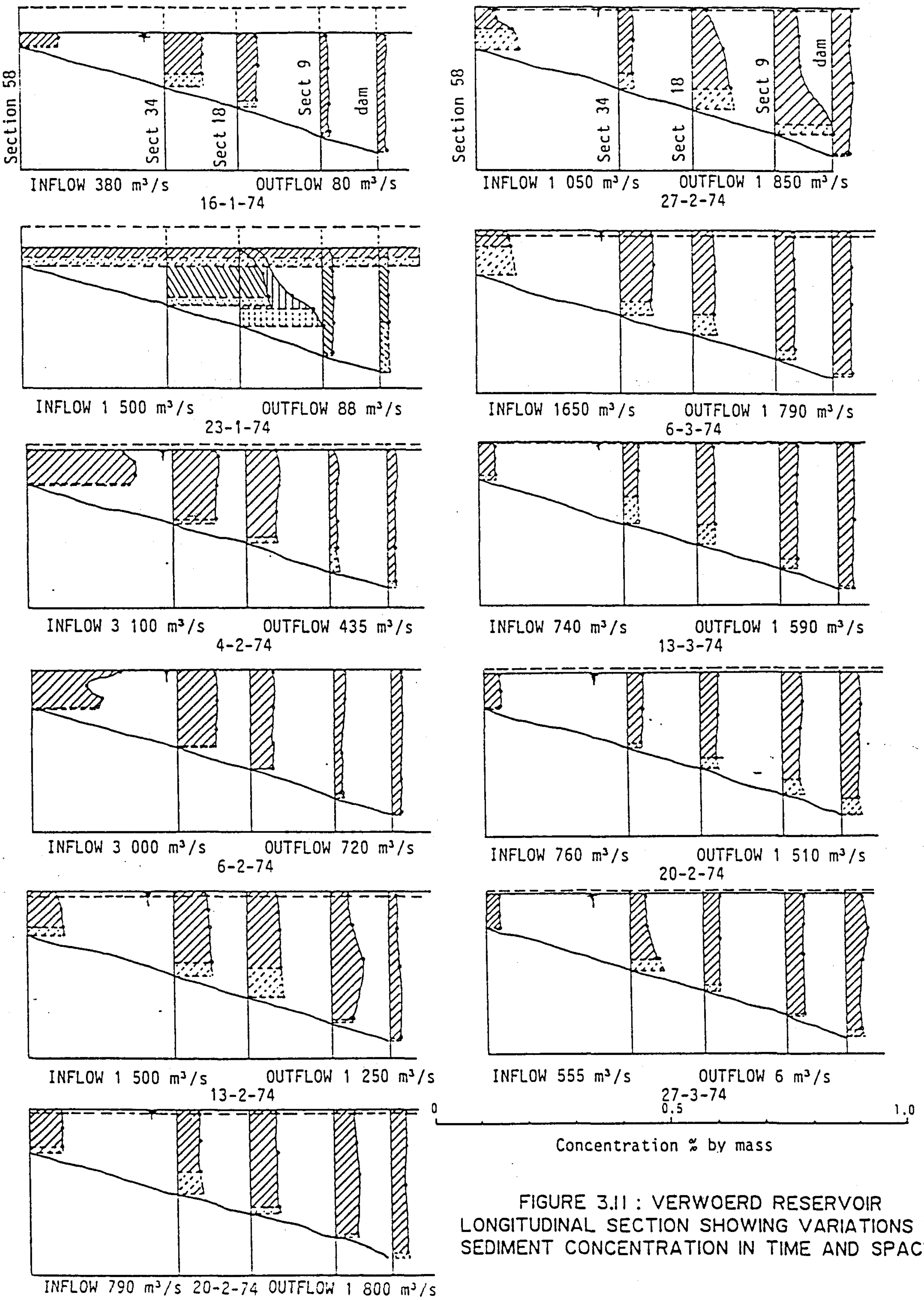
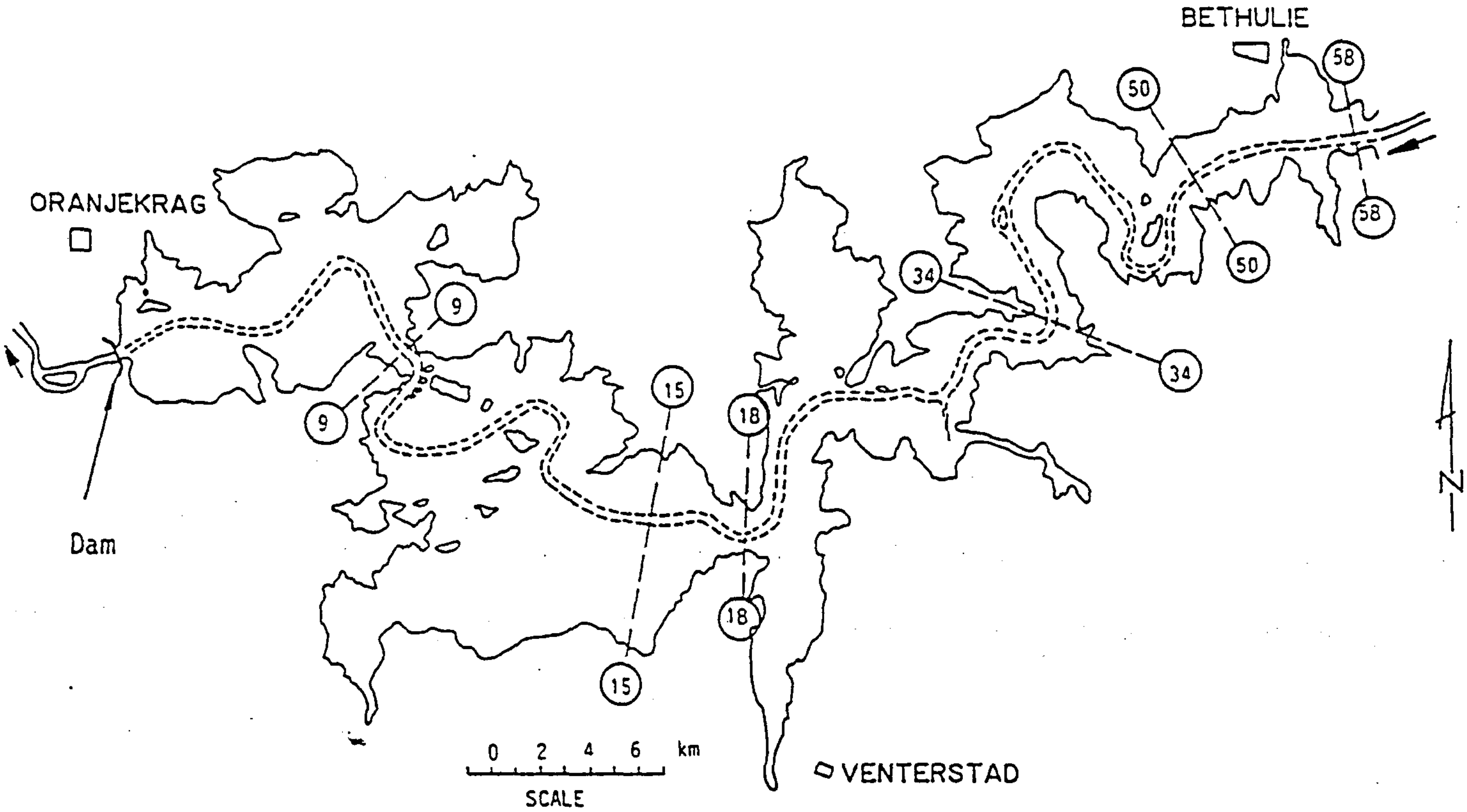



FIGURE 3.11 : VERWOERD RESERVOIR LONGITUDINAL SECTION SHOWING VARIATIONS IN SEDIMENT CONCENTRATION IN TIME AND SPACE




HENDRIK VERWOERD RESERVOIR PLAN

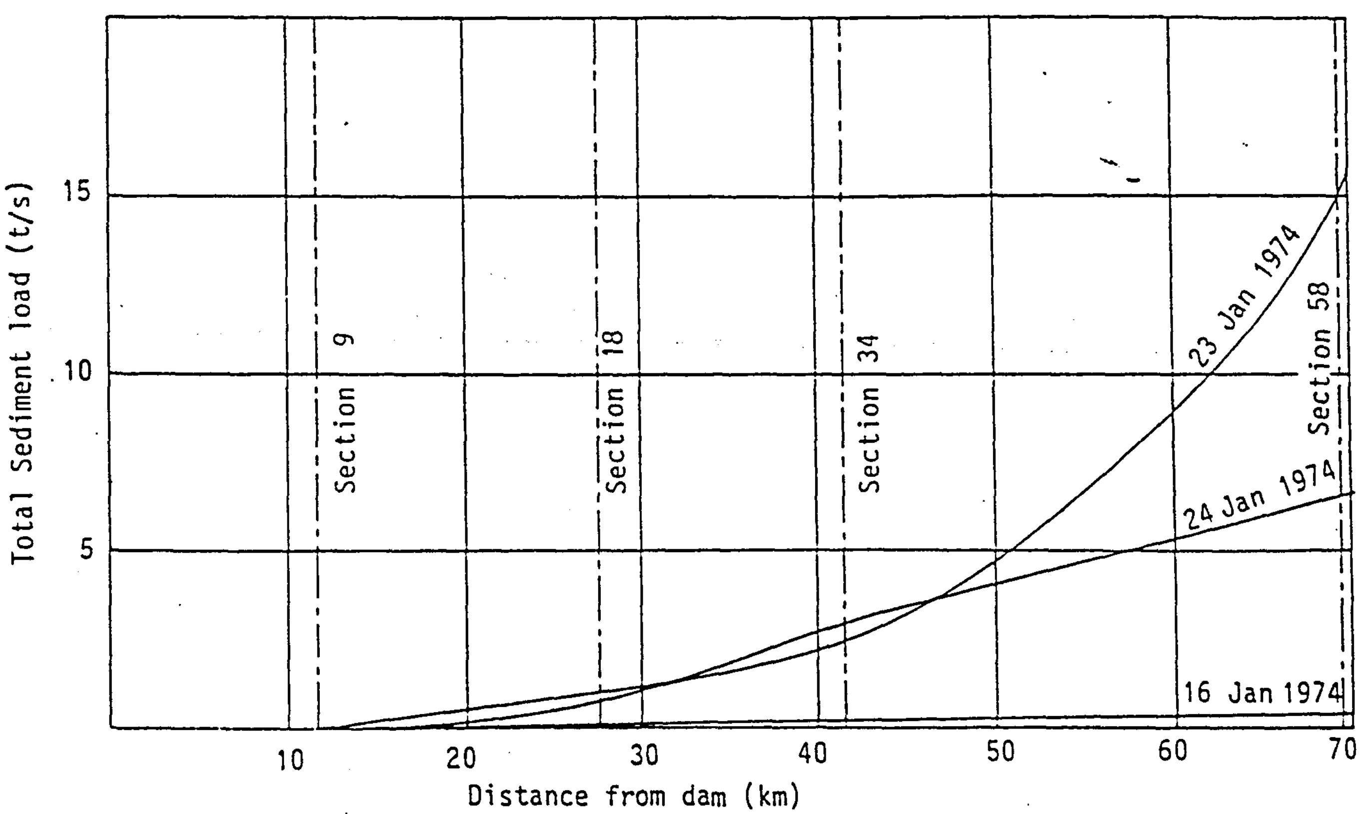



FIGURE 3.12 : HENDRIK VERWOERD RESERVOIR
SEDIMENT LOADS VS DISTANCE FROM DAM

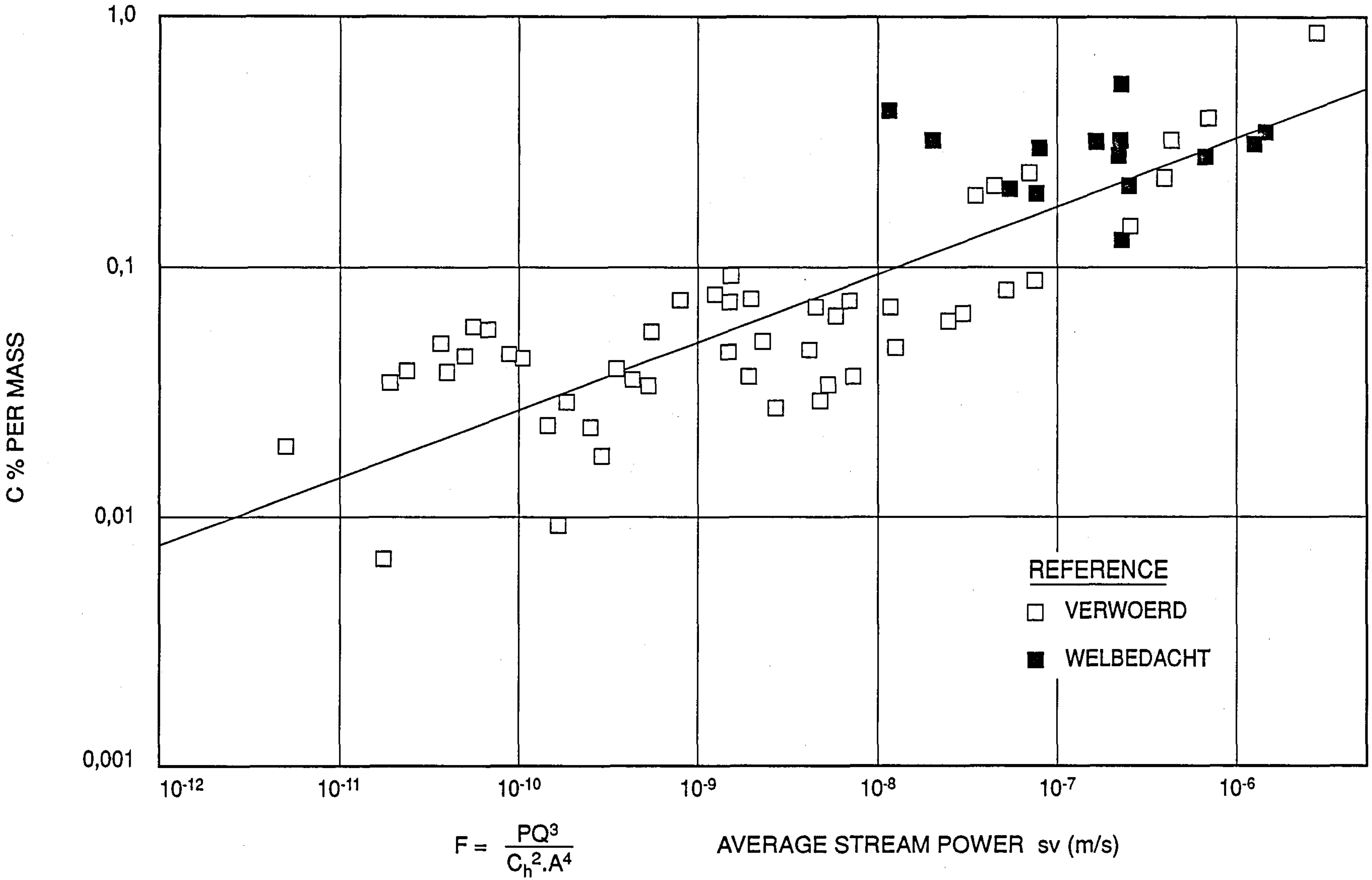



FIGURE 3.13: SEDIMENT CONCENTRATION VS STREAM POWER FOR FLOW THROUGH RESERVOIRS

Density currents can only be instrumental in transporting quantities of sediment while sediment is being introduced in high concentration. This only occurs when inflows into a reservoir are high and are likely to penetrate deep into a reservoir. Therefore, the role of density currents in moving sediment forward cannot be regarded in isolation from turbulent flows but must be weighed against that of turbulent suspension.

Conditions which are conducive to the formation of density currents may be analyzed as follows: (Rooseboom, 1975)

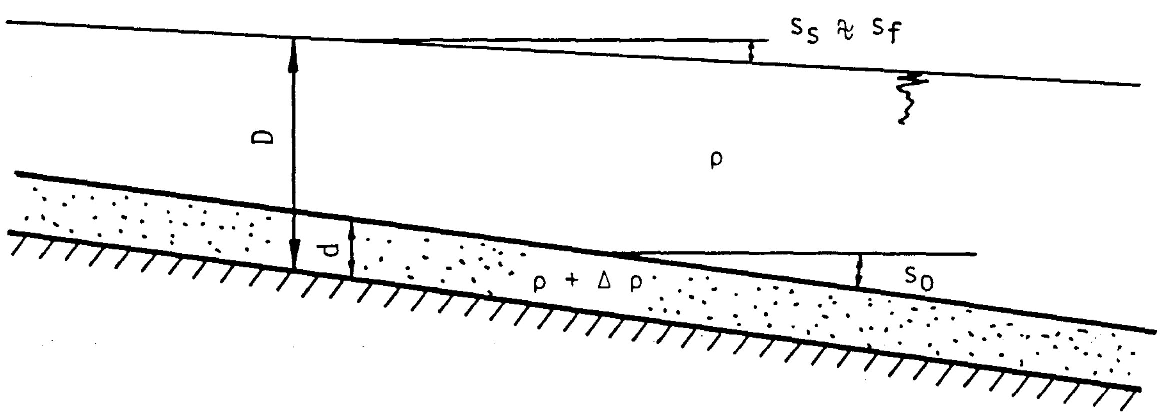



FIGURE 3.14 : DEFINITION SKETCH: DENSITY CURRENTS

$s_f$ = slope of energy line

$s_s$ = slope of surface line

$s_o$ = bed slope

$\rho$ = mass density of upper fluid

$\rho + \Delta\rho$ = mass density of density current

Consider a fluid element with density $\rho + \Delta\rho$ beneath a non-uniform fluid layer of density $\rho$.

Under normal turbulent flow conditions, the element with length $\Delta x$ moves forward as a result of the pressure difference which exists across the element.

$$\Delta p = \rho g s_s \cdot \Delta x$$

In situations where density currents occur, the value of $s_s$ is small and $\approx s_f$. The "turbulent" pressure on the element therefore $\approx \rho g s_f . \Delta x$.

Due to the existing density difference, an additional pressure difference is generated across the element. This pressure difference = $\Delta \rho g s_o \Delta x$.

$$\text{The ratio } \frac{\text{density pressure}}{\text{turbulent pressure}} = \frac{\Delta \rho \cdot s_o}{\rho \cdot s_f}$$

indicates the relative importance of density differences in the forward propulsion of sediments through reservoirs.

However, $s_f = \dfrac{v^2}{C_h{}^2 R}$ (Chézy equation)

where

$v$ = average flow velocity
$C_h$ = Chézy roughness coefficient
$R$ = hydraulic radius

(or: $s_f = \dfrac{v^2 n^2}{R^{4/3}}$) (Manning equation) where n = Manning roughness coefficient

$$\therefore \quad \frac{\Delta \rho}{\rho} \cdot \frac{s_o}{s_f} = \frac{\Delta \rho s_o C_h^2 . R}{\rho v^2} \quad \left(\text{or } \frac{\Delta \rho s_o R^{4/3}}{\rho v^2 n^2}\right)$$

Density differences will therefore play an important role relative to turbulent suspension if the value of the parameter

$$\frac{\Delta\rho S_o C_h^2 R}{\rho v^2} \quad \left( \text{or} \quad \frac{\Delta\rho s_o R^{4/3}}{\rho\, v^2 n^2} \right)$$

is high, i.e. in cases of:

(i) large density differences
(ii) large flow depths
(iii) steep bed slopes
(iv) low flow velocities

Density currents occur primarily on the steep (foreset) slopes of the deposits within the delta portion of very large reservoirs. Where they occur within deep reservoirs with steep bed slopes, large concentration differences can be identified e.g. in Sautet Reservoir (Figure 3.15). Conditions in existing southern African reservoirs are not conducive to the formation of sediment-laden density currents and no convincing evidence of such currents has been found.

Colloidal suspension refers to suspension of very small, discrete particles due to electro-magnetic interaction on a molecular scale. Sediment concentration in colloidal suspensions are determined by the availability of small particles as well as the chemical and physical charateristics of the suspension.

The very small particles (typically up to a few microns in size) tend to remain in suspension for long periods unless the interactive forces are neutralized, e.g. where a sediment laden river stream enters the ocean.

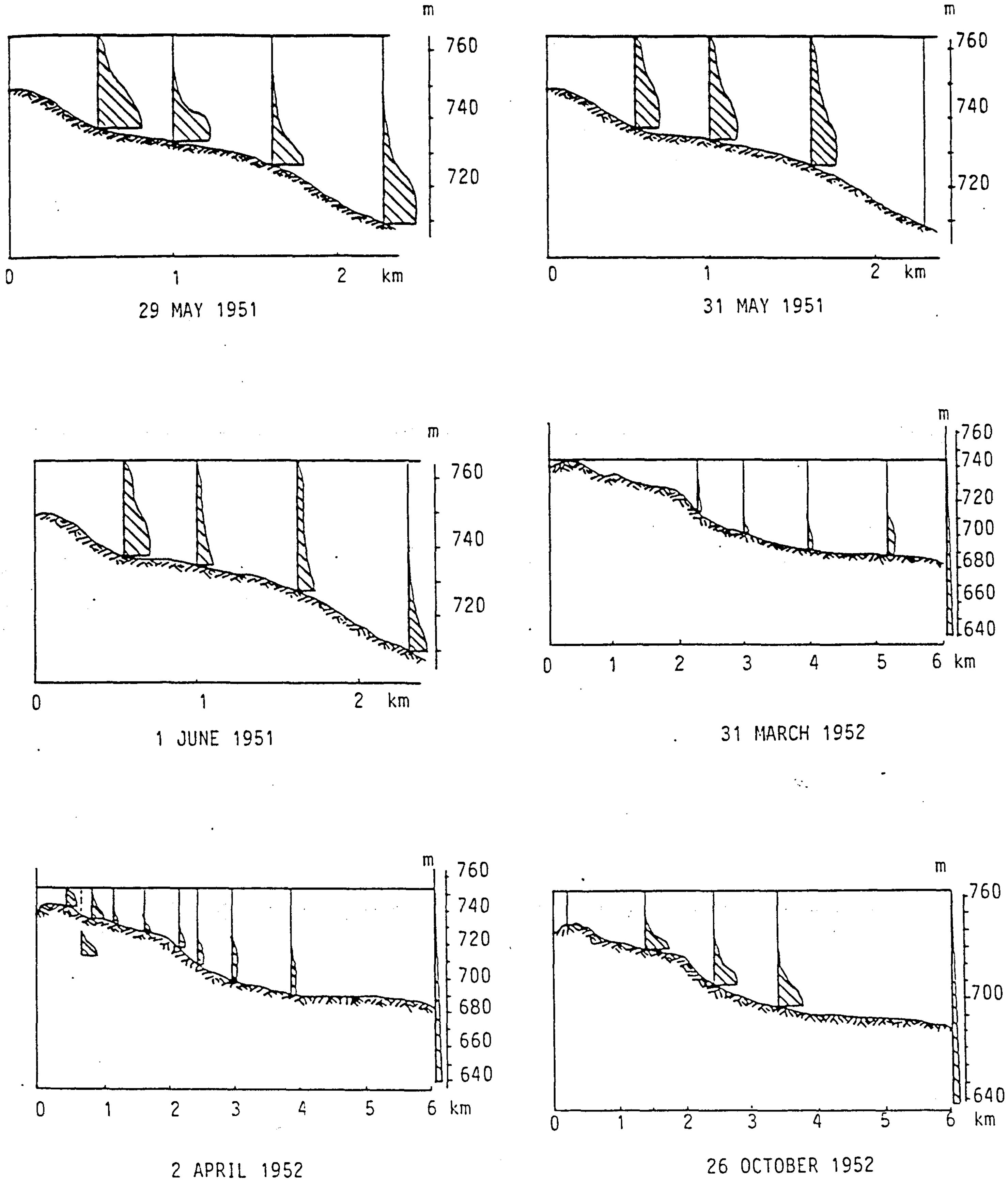



FIGURE 3.15

VARIATIONS IN SEDIMENT CONCENTRATION IN TIME AND SPACE
SAUTET RESERVOIR, FRANCE

Unless density currents develop, it is practically only the particles carried in colloidal suspension which pass through large storage reservoirs. Typically, the quantity thus passing through amounts to no more than a few percent of the total load which enters the reservoir.

## 3.11 A sediment load formula for sediment discharge from catchments

### 3.11.1 Introduction

In modelling sediment yields from small catchments the yields are normally linked to the run-off transporting capacity. The best known and most widely applied fromula in this field is the Universal Soil Loss Equation (USLE). This equation is still meant only for use on catchments with sizes up to "a few hundred hectares" (Lane et al, 1988).

In order to determine whether sediment yields from large catchments could be modelled in terms of the transporting capacity of catchment run-off it was necessary to develop the necessary mathematical formulae as no existing model could be found which would be suitable for application to large catchments in southern Africa.

Given the satisfactory results which have been obtained in modelling sediment transport ranging from erosion initiation through to suspended transport through reservoirs in terms of power concepts, this approach was also used to express catchment run-off transporting capacity.

### 3.11.2 Derivation of the transport formula

Consider a catchment strip of unit width and length L. If the runoff producing rainfall intensity is i and the runoff coefficient $C_r$ then the discharge per unit width

$$q = C_r.i.L \quad \text{.................................} \quad (3.40)$$

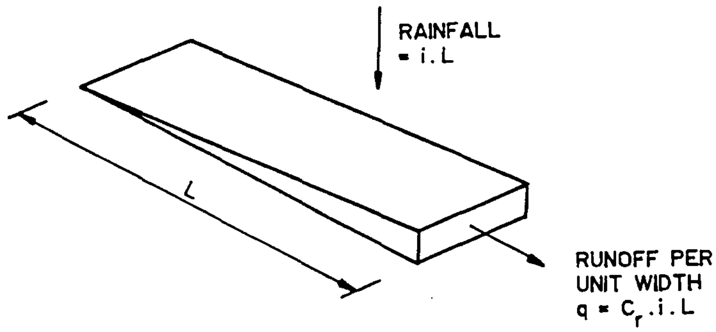



FIGURE 3.16

If it is assumed that this runoff flows uniformly (which is reasonable, where slopes are not steep because of the relatively high resistance), then

$$q = v.y = C_h \sqrt{ys}.y \quad \text{........................} \quad (3.41)$$

in terms of the Chézy equation where $C_h$ = Chézy roughness coefficient, y = depth of flow and s = slope.

Equation 3.40 represents the continuity equation or law of conservation of mass and the Chézy equation represents the special form of the energy equation, (Bernoulli equation valid for uniform one-dimensional flows).

It has been shown theoretically (Rooseboom, 1975) and statistically (Yang, 1972) that the sediment carrying capacity of a stream through turbulent suspension can be expressed by means of the equation:

$$C_s = \alpha(sv)^z \qquad \text{(See equation 3.35)}$$

$$\therefore C_s = \alpha(sv)^{\frac{\beta V_{ss}}{\sqrt{gys}}} \quad \text{.........................} \quad (3.42)$$

with $\alpha$ and $\beta$ = coefficients
$C_s$ = average sediment concentration
$s$ = slope
$v$ = flow velocity (average)
$V_{ss}$ = settling velocity of particles
$y$ = depth of flow

The sediment load per unit width ($q_s$) accordingly becomes

$$q_s = C_s.q$$

$$\begin{aligned}\therefore q_s &= \alpha(sv)^z q \\ &= \alpha(sv)^z.q \\ &= \alpha(s.C_h\sqrt{ys})^z.q\end{aligned}$$

from 3.41 $\sqrt{ys} = \left(\frac{qs}{C_h}\right)^{1/3}$

$$\therefore q_s = \alpha\left[s.C_h.\left(\frac{qs}{C_h}\right)^{1/3}\right]^z.q$$

$$= \alpha s^{\frac{4z}{3}}.C_h^{\frac{2z}{3}}\, q^{\left(\frac{z+1}{3}\right)}$$

with $z = \dfrac{\beta V_{ss}}{\sqrt{qys}} = \dfrac{\beta V_{ss}}{\sqrt{g}}\left(\dfrac{C_h}{qs}\right)^{1/3}$

and $q = C_r.i.L$

If it is assumed that the Chézy roughness coefficient $C_h$, the particle dimensions as represented by $V_{ss}$, the runoff coefficient $C_r$ are all constant for a given homogeneous sediment yielding region then

$$q_s = As^{\frac{4z}{3}} q^{(\frac{z+1}{3})}$$

with $z = B(qs)^{-1/3}$
and $q = Ci$

for a given fixed distance from the upper end of the catchment strip. If this distance is taken as unity then $q_s$ represents yield per unit area of catchment.

With the values of s and i known for a given area the sediment yield which is being transported in turbulent suspension can thus be calibrated in terms of the coefficients A, B and C.

A is representative of the availability of sediment, z represents sediment carrying capacity and C = run-off coefficient.

# 4. SEDIMENT TRANSPORT PATTERNS OBSERVED IN SOUTHERN AFRICAN RIVERS

## 4.1 Introduction

After more than 20 years involvement with sediment load data for southern African riviers, the main impression which remains is the variability thereof.

Not only are daily loads of rivers extremely variable but even on an annual basis the variability is such that longterm records are required in order to establish accurate estimates of average annual loads.

It is therefore extremely risky to draw conclusions from limited records.

## 4.2 Variability of daily sediment loads

The sediment loads of inland rivers in southern Africa consist mainly of particles smaller than 0,2 mm in diameter. These loads are carried in near-homogeneous suspension by flood discharges in rivers (See Sections 2.3.3 and 3.8).

Sediment particles are initially entrained either by overland sheet flow or minor streams where the carrying capacity becomes sufficient to transport the particles (Chapter 3.7). From this point the carrying capacity per unit volume of fluid tends to increase downstream except where significant retardation takes place. By the time the transported sediments reach main river courses, the carrying capacity tends to be far greater than that which is required to transport the sediment load which is being fed in to the courses so that the availability of sediment for transport is the limiting factor in determining the actual load where mainly fine sediments are being transported. This is accentuated by the fact that river beds consist mainly of coarser materials which are not brought into suspension as readily as finer particles.

Figure 4.1 depicts the scatter observed when recorded daily sediment concentrations are plotted against discharge for typical rivers which carry fine sediments. It does not make much sense to draw a single line through these points in order to obtain a so-called rating curve. Double mass curves, which will be described further on, provide more meaningful relationships for determining average sediment loads where these loads are carried mainly in suspension.

### 4.3 Variations in annual sediment loads

Even on an annual basis the sediment loads carried by rivers tend to be highly variable.

The most comprehensive long term record of the load being carried by a river on an annual basis in southern Africa is the combined record for the gauging stations at Prieska and Upington on the lower Orange River. Although these stations are some distance apart, little sediment is fed into the Orange River between them. Their sediment load records may therefore be combined to form a continuous record for the period 1929 - 1969.

These data have been plotted in the form of cumulative sediment discharge vs time (Figure 4.2) as well as 10 year moving averaged values vs time (Figure 4.3).

The following observations can be made from these figures:

(i) Annual loads vary greatly (Figure 4.2). The load carried during the hydrological year 1933 - 1934 of 282,4 million tonne was for instance 25 times

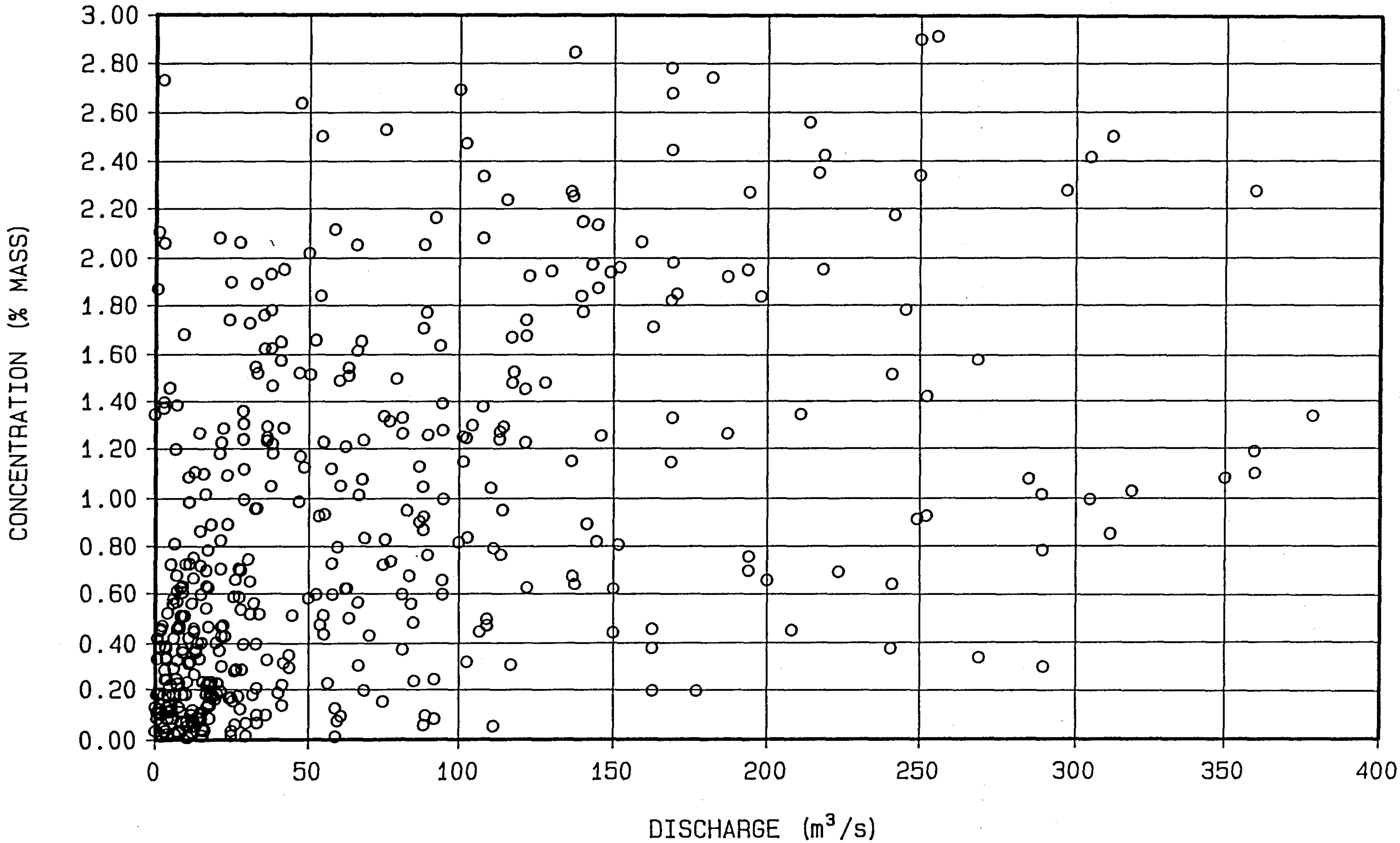



FIGURE 4.1 : CALEDON RIVER AT JAMMERSDRIFT : MAY 1969 - MAY 1976 : MEASURED SUSPENDED SEDIMENT CONCENTRATION : DISCHARGE

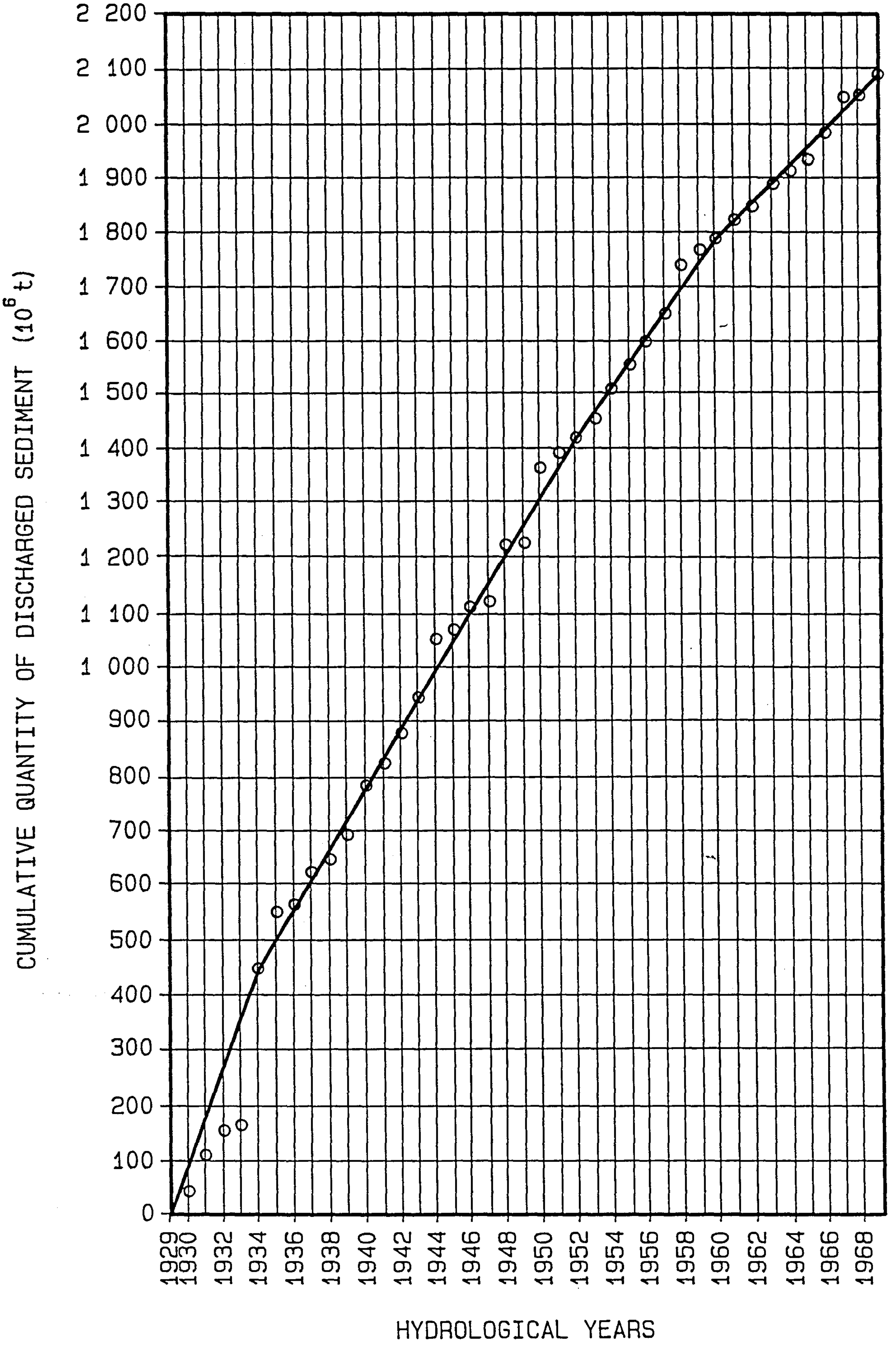



FIGURE 4.2 : CUMULATIVE SEDIMENT DISCHARGE
ORANGE RIVER BASIN : 1929 - 1969

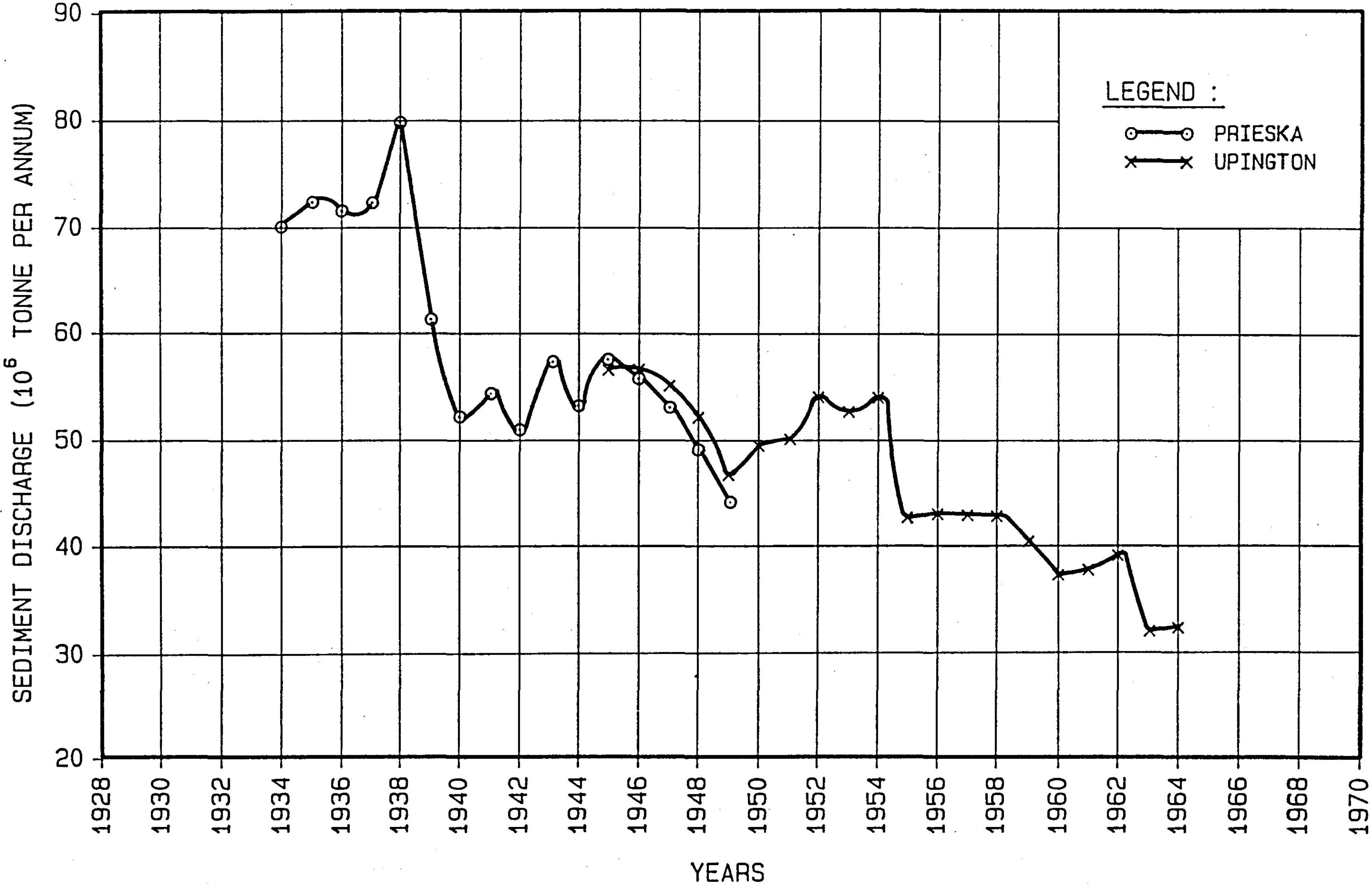



FIGURE 4.3 : 10 YEAR MOVING AVERAGES OF SEDIMENT DISCHARGE FOR THE ORANGE RIVER CATCHMENT : COMBINED DATA FOR PRIESKA AND UPINGTON

greater than that of 11,2 million tonne for the previous hydrological year. According to the original records the load carried during a specific day during 1933 - 1934 was in excess of 25 million tonne i.e. more than would be carried in many a year.

(ii) Even when the 10 year moving average is plotted (Figure 4.3) a large degree of variability is evident.

(iii) Both Figures 4.2 and 4.3 indicate that the average sediment load decreased by more than 50% during the period 1929 - 1969. This decrease has been attributed mainly to a decrease in the availability of erodible soils (Rooseboom and Harmse, 1979). Significant changes in average loads have also been deduced for other catchments from reservoir surveys, but these cannot be quantified with the same degree of accuracy. Table 4.3.1 contains most of the sediment loads, derived from the original raw data for the Orange River System. Further information is included in Table 5.2.2. (Rooseboom, 1975).

## 4.4 Determination of average annual sediment loads from stream sampling records

Where continuous sediment sampling has been undertaken for a very long period it is relatively easy to obtain representative average yield values for different periods and to identify periods during which averaged loads tended to be constant (Figures 4.2 and 4.3).

Typically however one is forced to draw conclusions regarding average loads from much shorter records.

It is common practice to draw a rating curve of sediment concentration as a function of discharge based on short term sampling and to use this rating curve in conjunction with longer term discharge records. A rating curve based on limited data may only be used where a singular relationship does exist between sediment concentration and discharge. Rating curves based on scattered data may only be used where long, continuous records exist and should only be used conjunction with flow records which cover the same period as the recorded sediment concentrations. In the latter case, the preparation of a rating curve is really meaningless and alternative calculation methods may as well be used.

The least meaningful calculations which have been performed regarding averaged sediment loads are those where sediment concentrations have been averaged without any reference to corresponding discharge values. In the end the averaged concentrations were multiplied with average discharge in order to obtain averaged sediment loads. Such calculations lead to results which are of little value.

Sediment concentrations tend to be high after long periods of low run-off from catchments and vice versa. This explains the stable progression of double-mass curves of cumulative sediment discharge versus cumulative water discharge (Figure 4.4).

The averaged slope of a double mass curve as depicted in Figure 4.4 represents the average sediment concentration. This value can be multiplied by the long term average annual run-off to obtain the average annual sediment load.

By determining the average slope of the best fitting line through points equidistant on the double mass curve this

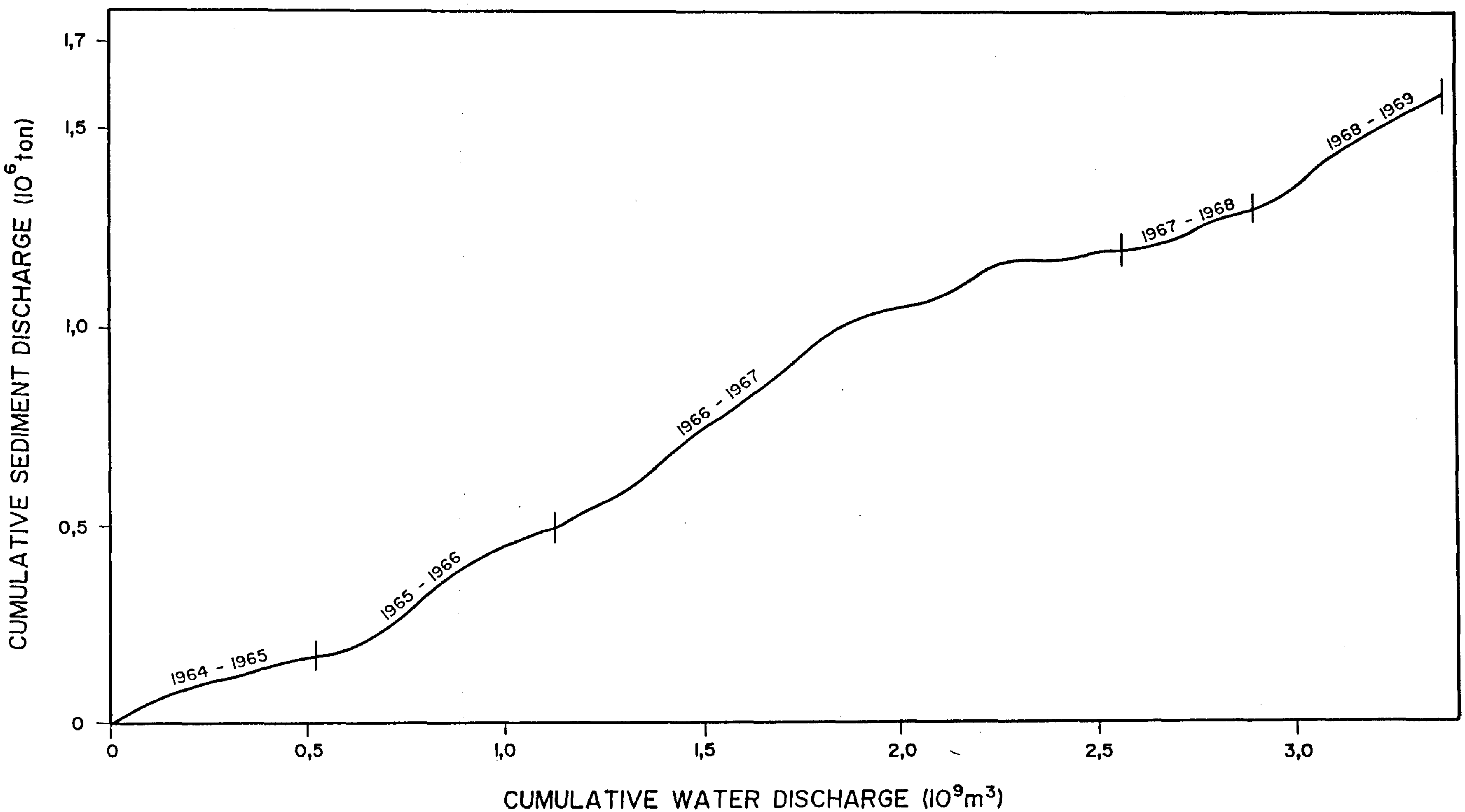



FIG 4.4 : CUMULATIVE SEDIMENT DISCHARGE VS CUMULATIVE WATER
BETHULIE BRIDGE OCT 1964 - SEPT 1969

average concentration can be determined. It is typically found that the slope after say five years of record changes very little.

Even when the average annual discharge during the record period differs from the long-term average, the average slope may be used together with the long term average discharge to obtain an accurate estimate of the average sediment load.

It is thus possible to obtain an accurate estimate of the average sediment load from continuous (daily) sampling records of 6 years and even less. This represents an enormous saving in time and costs relative to if say the averaged load is taken as the arithmetic mean of the individual annual loads in which case longer sediment records are required to obtain meaningful results (compare Figure 4.3).

## 4.5 Determination of average sediment loads from re-surveys of reservoir sediment deposits

Very little continuous (daily) sampling of sediment loads in rivers has been undertaken in South Africa since 1971. This can be attributed to the facts that

(i) the collection and processing of daily samples is costly and cumbersome.

(ii) regular resurveying of existing reservoirs is being done very efficiently by the Department of Water Affairs and the number of reservoirs being covered provides a wide spectrum of catchments for which sediment yields can be determined with relative ease and at limited cost.

Advantages of sediment loads and yields being derived from re-surveys of sediment deposits in reservoirs are:

(i) The speed and the ease with which such surveys can be performed.

(ii) The accuracy with which total loads can be measured, provided that the original surveys were accurate and provided that trap efficiencies can be determined accurately.

(iii) The fact that the most critical periods of data collection i.e. peak flood discharges after long dry spells do not pose monitoring problems.

When sediment loads and yields are to be derived from reservoir re-surveys care should be taken:

(i) not to use deposits younger than 8 - 10 years.

(ii) to include deposits above the full supply level in the calculations where available.

(iii) not to use information for smaller reservoirs with ill-defined trap efficiencies.

(iv) to consider hydrological occurrences during the period of accumulation. A major flood occurring shortly before a re-survey may lead to an over-estimation of the mass of accumulated sediment due to the fact that only limited consolidation of the fresh deposits is likely to have taken place.

A critical component of the conversion of sediment deposit volume into mass is the variable density of sediment deposits.

In order to overcome the uncertainties which are involved, an indirect method has been developed for converting volume into mass which circumvents the practical problems involved in estimating the average density of the deposit at a given stage.

Assuming that a logarithmic relationship exists between sediment deposit volume and time, (Rooseboom, 1975) it was found that for a number of South African and USA reservoirs it was possible to express the volume of a sediment deposit after t years ($V_t$) as a fraction of the volume after 50 years ($V_{50}$) by means of the relationship (Figure 4.5 and 4.6)

$$\frac{V_t}{V_{50}} = A \ln \frac{t}{B}$$

and the following ratios were obtained from the relationships:

| Reservoir | Land | Original Volume ($10^6 m^3$) | $V_{50}$ ($10^6 m^3$) | $\frac{V_{10}}{V_{50}}$ | $\frac{V_{20}}{V_{50}}$ | $\frac{V_{100}}{V_{50}}$ |
|---|---|---|---|---|---|---|
| Elephant Butte | USA | 3 249 | 627 | 0,46 | 0,69 | 1,23 |
| Theodore Roosevelt | USA | 1 877 | 186 | 0,45 | 0,69 | 1,24 |
| Lake Mentz | RSA | 308,6 | 102 | 0,35 | 0,63 | 1,28 |
| Lake Arthur | RSA | 102,9 | 89,3 | 0,39 | 0,66 | 1,27 |
| Lake Mac Millan | USA | 112,2 | 67,8 | 0,36 | 0,63 | 1,25 |
| Gournsey | USA | 91,0 | 45,8 | 0,36 | 0,64 | 1,28 |
| Grassridge | RSA | 89,6 | 37,0 | 0,38 | 0,65 | 1,27 |
| Van Ryneveldspas | RSA | 81,4 | 28,5 | 0,39 | 0,65 | 1,25 |
| Prinsrivier | RSA | 4,9 | 2,9 | 0,37 | 0,64 | 1,26 |
| AVERAGED VALUES | | | | 0,39 | 0,65 | 1,26 |

TABLE 4.1: THE VOLUME OF THE SEDIMENT DEPOSIT AFTER t YEARS AS A FRACTION OF THE VOLUME AFTER 50 YEARS

Based on the averaged values
Values of A = 0,376
and B = 3,5

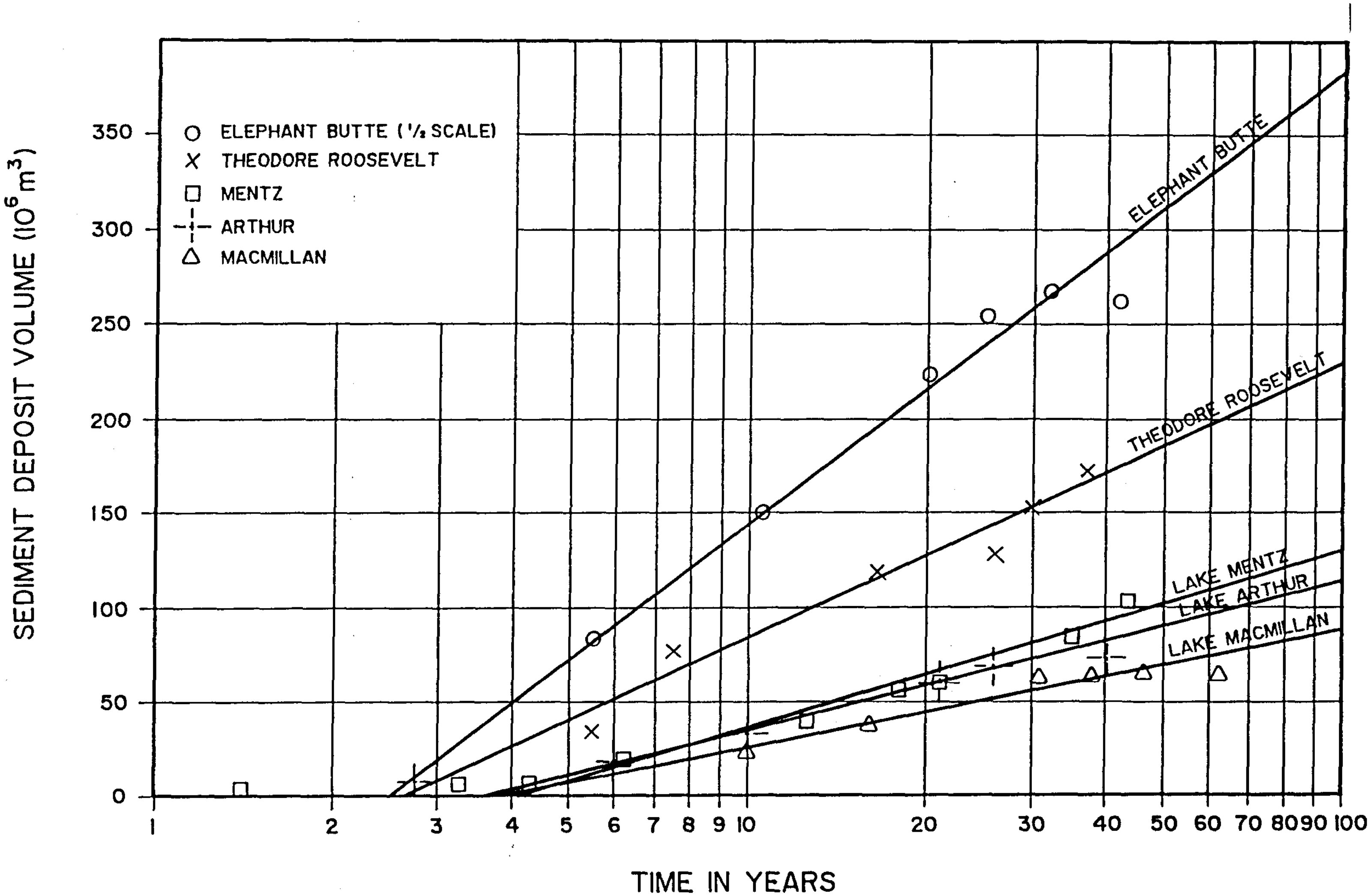



FIG 4.5 : SEDIMENT ACCUMULATION WITH TIME

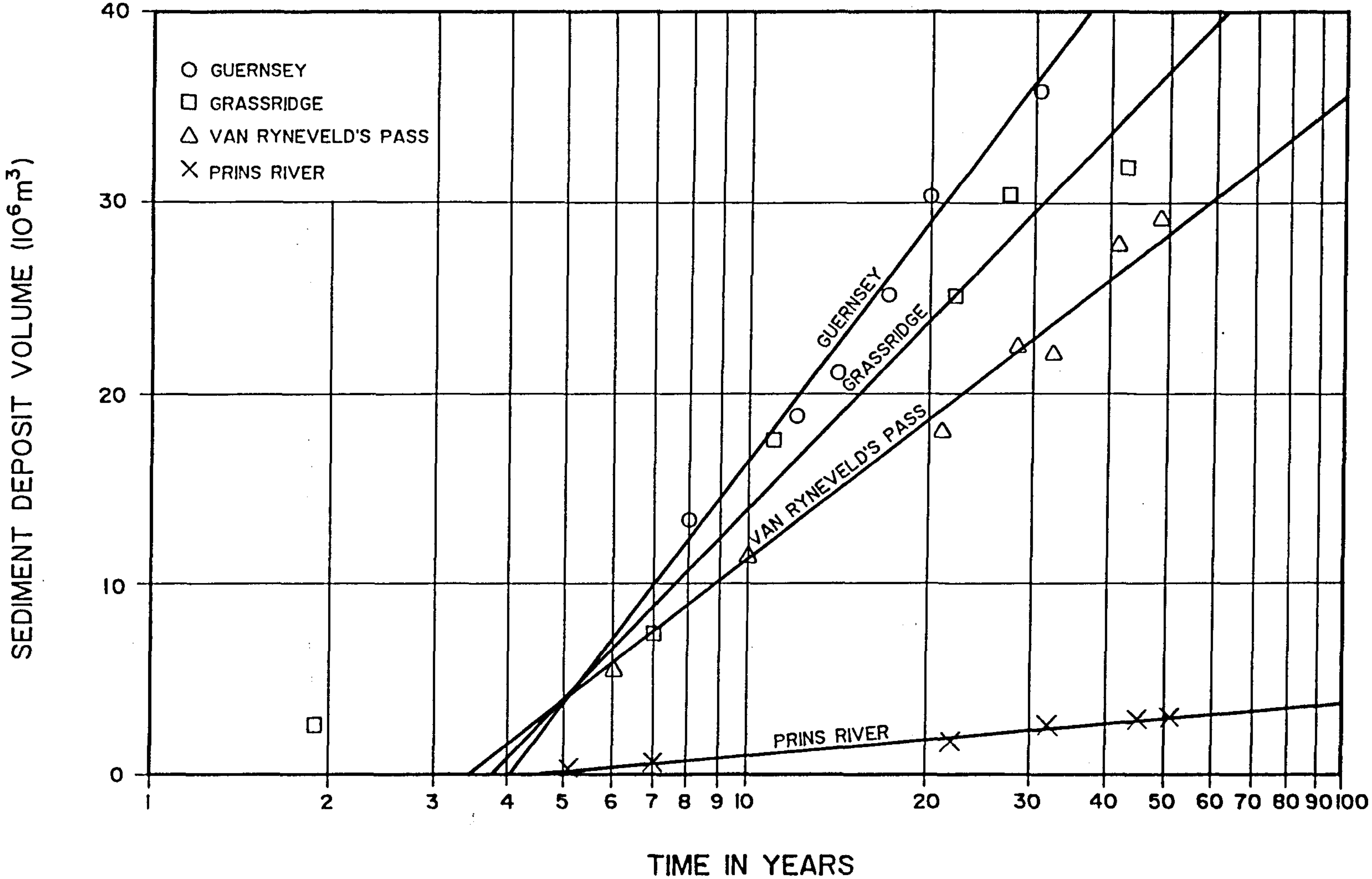



FIG 4.6 : SEDIMENT ACCUMULATION WITH TIME

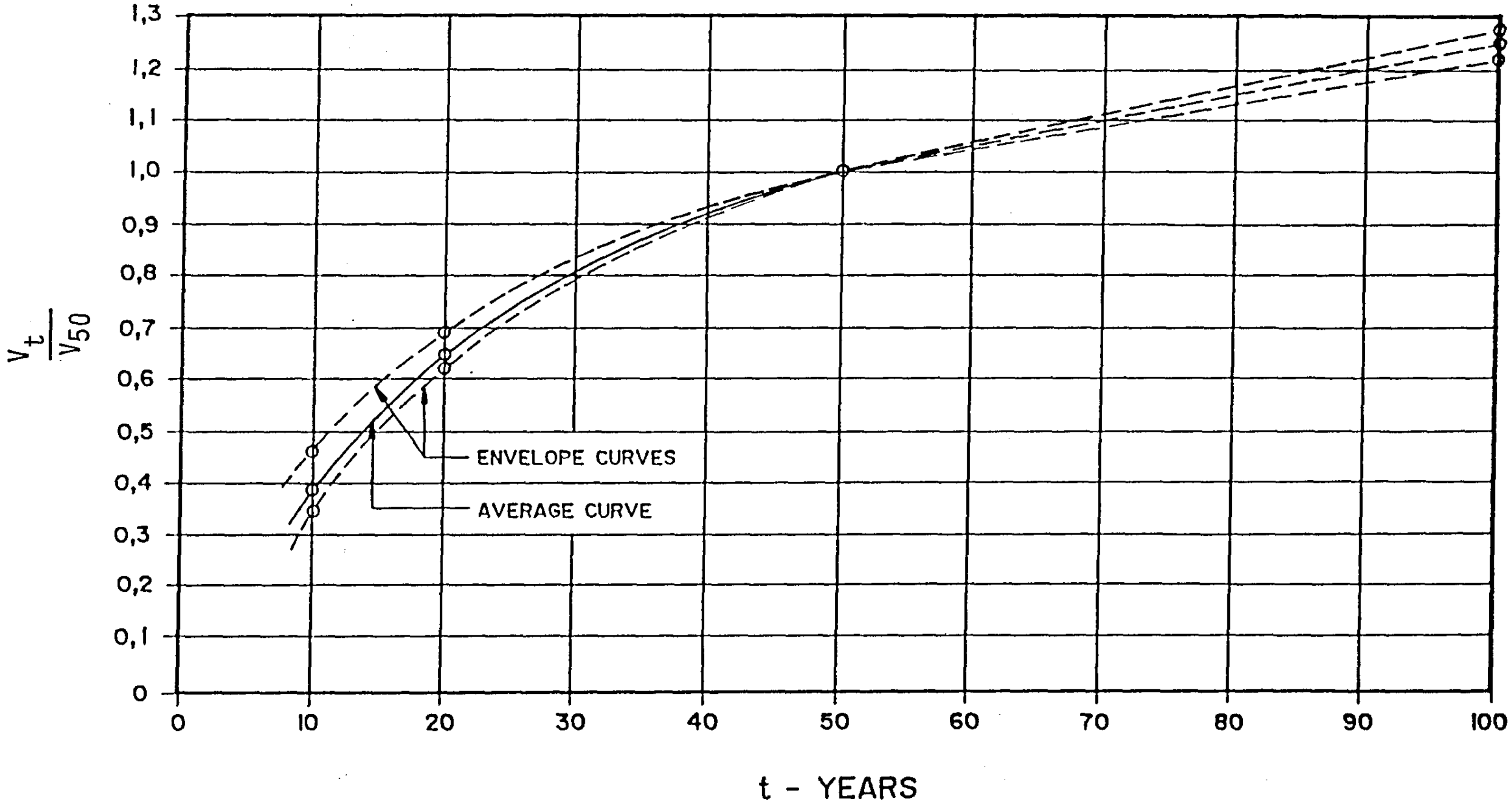



FIG 4.7 : SEDIMENT DEPOSIT VOLUMES AFTER t YEARS AS FRACTIONS OF THOSE AFTER 50 YEARS

were subsequently adopted for calculation purposes (Figure 4.7). It is thus possible to convert the 50 year volume into the volume after t years and vice versa.

The 50 year reference volume was chosen for the following reasons:

After 50 years of accumulation the density of the deposit can be calculated with a fair degree of confidence because

(i) consolidation takes place at a relatively low rate.

(ii) density does not vary much as a function of the composition of the deposited materials (i.e. % sand, silt, clay).

(iii) sufficient historical data is available for estimating average densities after 50 years.

A value of 1,350 $t/m^3$ is commonly used in South Africa as the average density after 50 years. Should this figure be in error, it is cancelled out when the derived information is used to calculate storage volume losses in reservoirs.

The most important usage of this type of calculation is for the prediction of storage volume losses and uncertainties regarding densities are thus circumvented.

# 5. SEDIMENT YIELD PATTERNS FOR SOUTHERN AFRICA: THE 1992 MAP (Rooseboom et al. 1992)

## 5.1 Introduction

It will be seen in Section 5.2, that sediment yield values vary greatly across southern Africa. In order to make maximum use of the limited recorded yield data, especially for purposes of predicting sedimentation rates in planned reservoirs, various sediment yield maps were produced in the past (Midgley (1952), Schwartz and Pullen (1966), Rooseboom (1978)).

Each of these maps was based on sub-division of southern Africa into zones of equal theoretical yield potential and subsequent calibration in terms of recorded yield values.

Steadily improving soil and other base maps as well as a rapidly expanding data base of sediment loads has made it possible and desirable to upgrade sediment yield maps virtually every 13 years since 1952.

From wide-ranging enquiries that were being received it was clear that the 1978 map (Figure 5.1) has been used and mis-used extensively. Whilst the map was intended to indicate maximum expected sediment yields in different areas, it has become evident that there is a need for more detailed information. It was therefore decided to approach the data analyses in a more sophisticated way in order to provide a more comprehensive picture of sediment yield values.

One of the practical problems encountered in the analysis of sediment yield data is that sediment yields not only vary in space but may also vary considerably with time as conditions change. Although there exists widespread evidence of such changes in southern Africa due i.a. to the depletion of readily erodible top-soils and increasing numbers of farm dams, it is difficult to quantify and to relate such changes to specific parameters. It takes some six years of continuous monitoring to obtain an accurate estimate of the average sediment load of a typical local river. Much longer records, are therefore required to identify persistent changes in yields.

Our data base was not comprehensive enough to incorporate the time dimension. We did however give priority to yields derived from reservoir surveys because these data were generally more recent than the yields derived from stream sampling.

In order to try and obtain meaningful relationships between recorded sediment yield values and the sediment yield characteristics of the catchments, three different approaches were used:

(a) Multiple Regression Analysis
(b) Deterministic Run-off Modelling
(c) Regionalized Statistical Analysis

The following variables were included in the analyses:

soil erodibility indices
land-use
slopes
rainfall intensity
rainfall erosivity indices

It can be argued that a number of other variables e.g. vegetation or biomass cover etc. should be included in such investigations. It is believed however that the above-mentioned parameters provide the best practical parameters for describing yield potential in southern Africa especially for larger catchments. The limited data base which is normally available for analyses on a country-wide basis severely limits the number of parameters which can be included.

## 5.2 Available data

The main data base used in the calibration of the sediment yield map consists of the reservoir survey records of the South African Department of Water Affairs. Data for 122 reservoirs was used to determine yields for the appropriate catchments. (Table 5.2.1) A number of reservoir sedimentation records had to be excluded from use because of the following problems:

(a) Uncertainty about trap efficiencies.
(b) Records which are too short (< 8 years).
(c) Inadequate accuracy of original surveys.

The catchments of the selected reservoirs cover some 260 000 $km^2$ (Figures 5.2 and 5.3) and the ages of the surveyed deposits varied between 8 and 82 years. In addition sediment yields determined from 22 sediment gauging stations representing catchments with a total area of 520 000 $km^2$ are available. (Table 5.2.2 and Figure 5.4) Once again only continuous daily records of sufficient length > 6 years were accepted. Shorter records (Makhoalibe, 1984) were used to determine relative yield values for different catchments in Lesotho.

Various base maps were prepared for the study. These included a basic erodibility map (Figure 5.5) based mainly on soil types which was eventually simplified to Figure 5.9, agricultural land-use regions (Figure 5.6) and an average slope map (Figure 5.7) as well as a rainfall erosivity map (Figure 5.8).

## 5.3 Multiple regression analyses

Assuming constant sediment yields for each of the original erodibility categories, a multiple linear regression model was used to solve sets of equations of the form:

$$Q_s = \alpha_1 A_1 + \alpha_2 A_2 + \alpha_3 A_3 + \ldots\ldots \alpha_n A_n$$

where $Q_s$ = total annual sediment yield of a catchment; $\alpha_1$, $\alpha_2$, $\alpha_3$ ... = unit yields ($t/km^2$. annum) and $A_1$, $A_2$, $A_3$ areas within the catchment of categories 1, 2, 3 etc.

With the $Q_s$ and A values known it was possible to write more than 120 equations with some 25 - 30 $\alpha$ values as unknowns, depending on the combinations of erodibility categories and land use that were selected. The combinations were tested on a national scale as well as on a regional scale.

The following problems were generally experienced:

(a) Very low levels of significance.
(b) Large standard errors of estimate.
(c) Existence of multi-collinearity.
(d) Negative unit yields were obtained in some cases.

The conclusion had to be drawn that there was a very high degree of variability in the unit sediment yields for regions which were deemed to deliver constant yields and that certain simplifying assumptions would have to be made in order to come to a workable solution. It was also necessary to determine whether unit yields for certain regions could be linked to the sediment-carrying capacity of catchment run-off. A deterministic model was developed for this purpose.

## 5.4 Deterministic model

One of the approaches used in the analysis was to develop a mathematical model (Section 3.11) which would describe the transporting capacity of run-off for different areas and to try and calibrate such a model for different areas of equal yield potential. This model was developed because no model could be found which was deemed suitable for large catchments, based on our previous attempts at modelling sediment discharge from large catchments.

Because of the satisfactory results which were obtained with the stream power approach in the analysis of erosion initiation (Rooseboom and Mülke, 1982) on the one hand and in modelling sediment movement through reservoirs on the other extreme (Rooseboom and Van Vuuren, 1988) this approach was used for depicting sediment carrying capacity of run-off.

The model was based on:

(a) the rational formula to determine run-off discharge.
(b) the continuity and Chézy equations to convert discharge into flow velocities and depths.
(c) a stream power equation to represent the sediment transporting capacity of the discharge.

The resulting equations read: (See 3.11)

$$q_s = A\ s^{4z/3}\ q^{(z+1)/3} \quad \text{with } z = B(qs)^{-1/3}$$

and $q = C\ i$

where A, B & C = empirical coefficients
i = rainfall intensity
q = runoff per unit width at a given distance
$q_s$ = sediment discharge per unit width
s = average slope (Figure 5.7)

A is representative of the availability of sediment, B = Representative of the sediment carrying capacity and C = run-off coefficient.

Although it is believed that the model provides a good mathematical description of the transport capacity of run-off, it was found impossible to calibrate the model with our data. Other transport models contain the same basic variables and should fare no better in terms of the data. Once again we have had to come to the conclusion that the availability of sediments and not the carrying capacity of run-off determines sediment loads in our rivers. This is understandable because a large proportion of the particles carried by most of our rivers is smaller than 0,2 mm in diameter. Winds play important intermediary roles during dry periods in transferring particles from high-lying to low-lying areas i.e. from areas where the carrying capacity of run-off is low to areas where it is high. Thus sediment accumulates in lower-lying areas to be picked up by the first significant run-off. During the long dry periods encountered in southern Africa the wind-borne sediment loads, which can be much greater than those carried by rivers, are therefore very significant in making sediment available for water-borne transportation at a later stage.

It is probably only in the very flat, dry areas of southern Africa where the sediment-carrying capacity of run-off rather than the availability becomes the limiting factor in determining the sediment loads of run-off. These are areas where yields are very low and where little data exists.

## 5.5 Simplified statistical analysis

### 5.5.1 Approach used

Following the disappointing results obtained from comprehensive multiple regression analysis and the clear indications that sediment yields could not be meaningfully linked to run-off transporting capacity, a simplified statistical approach had to be followed in order to produce practical results.

Firstly, the sub-continent had to be divided into regions with relatively uniform yield potential. The regional boundaries (Figure 5.9) were established after consideration of:

(a) A basic yield index map based primarily on soil types and slopes, prepared by Prof E Verster.
(b) Land-use
(c) Availability of recorded yield data.
(d) Boundaries of river catchments.
(e) Rainfall characteristics.

Following preliminary analyses of the yield data in terms of the yield index map, the number of sub-divisions was decreased and each of the nine main regions was sub-divided into sub-regions with higher, medium and lower sediment yield potential.

In order to overcome the problems experienced when multiple regression analyses were performed, it was assumed that for a given region, the ratios between the yields for its higher, medium and lower sub-regions are constant. We believe that this is the only practical way of resolving the problem of the high degree of variability encountered in sediment yields even from seemingly identical catchments. Constant ratios between yields from sub-regions exist by implication in all calibrated maps. The adopted ratios were determined by calculating the ratios between median recorded yield values for representative catchments falling within the sub-regions.

By using these ratios, a standardised yield value could be calculated for each reservoir catchment, equivalent to the yield which would have been recorded if the catchment had consisted only of medium potential sub-catchments. Statistically, the logarithms of the standardised yield values conformed to a generalised extreme value distribution with negative skew (negative Weibull distribution).

As it may be expected that the variation in yield values will decrease within a region with increasing catchment size, recorded yields were analysed in terms of catchment size. Where sufficient data was not available for clear determination of such trends, the same multiplying factors are given irrespective of catchment size.

For the determination of sediment yield values in Southern African catchments, the following tools are used:

(i) A map of Southern Africa, on which nine distinct sediment yield regions are indicated. The map also divides the sediment yield potential of the soils in each of the regions into three categories of higher, medium and lower sediment yield potential (Figure 5.9).

(ii) A table containing mean standardized sediment yield values for each of the nine sediment yield regions (Table 5.5.1).

(iii) Graphs showing, for each region, the variability displayed by existing data, linked to catchment size.

(iv) A table with sediment yield factors for each region, by means of which the standardized sediment yield values can be converted to weighed average yield values for any given catchment (Table 5.5.1).

### 5.5.2 Methodology for applying the map

Firstly determine the regional standardized sediment yield value, which is applicable to a catchment with a specific size and location, and then convert this value into the actual yield value, taking into account the actual yield potential of the different soils in the catchment.

The method consists of the following steps:

(i) Determine the location and the size of the catchment for which the estimated sediment yield is to be determined.

(ii) Obtain from the sediment yield region map, the yield region (from 1 to 9) for the catchment as well as the sizes of sub-areas within the catchment which consist of soils with different yield potential (higher, medium and lower yield potential) (Figure 5.9).

(iii) For the given region, use the regional standardized mean yield given in Table 5.5.1.

(iv) From the graph for the region, (Figures 5.10 - 5.17) select the multiplying factor with due consideration of catchment conditions. Note that the factors given are envelope values, and are expressed as multiples of the regional average standardized sediment yield.

(v) Convert the standardized sediment yield values to site specific yield values with the formula:

$$Y_C = Y_S \left[F_H \frac{AH}{A_T} + F_M \frac{AM}{A_T} + F_L \frac{AL}{A_T}\right]$$

with

$Y_C$ = estimated catchment sediment yield value ($t/km^2.a$).

$Y_S$ = standardized sediment yield value ($t/km^2.a$)

$F_H$ = high yield potential factor (Table 5.5.1)

$F_M$ = medium yield potential factor (Table 5.5.1)

$F_L$ = low yield potential factor (Table 5.5.1)

$A_H$ = size of area consisting of soils with high sediment yield potential ($km^2$)

$A_M$ = size of area consisting of soils with medium sediment yield potential ($km^2$)

$A_L$ = size of area consisting of soils with lower sediment yield potential ($km^2$)

$A_T$ = Total catchment area ($km^2$)

(vi) It will always be necessary to consider existing conditions within the catchment when estimates are being prepared and also to compare the value obtained to recorded yields for comparable catchments.

### 5.5.3 Specific aspects to be considered when estimating sediment yields for each region

**Region 1**

The region consists of drainage regions of the Transvaal rivers which flow to the Indian Ocean, mainly the tributaries of the Limpopo river.

Sufficient data is available for the region for drawing conclusions regarding the effect of catchment size. Sediment yield data obtained from reservoir surveys are available for 31 sites, with record lengths that vary in length from 12 to 60 years.

The majority of catchments with sediment yield information are situated in the upper regions of the Marico, Olifants and Crocodile river catchments. Little data is available for areas in the far northern Transvaal, near the main branch of the Limpopo.

The region is geologically diverse. The land use varies and includes highly urbanized areas, cattle and maize farming, as well as some subsistence farming areas.

Nevertheless, the measured sediment yield values show a strong tendency to converge to a regional mean value with increasing catchment size. This can be seen from the graph showing confidence limits linked to catchment size for Region 1 (Figure 5.10).

Developing and highly urbanized and industrialized areas in this region have to be carefully considered, as these areas produce high sediment yields. An example is the Hartebeespoort Dam. Even though this reservoir has a large catchment, the sediment yield is exceptionally high for the region. This is attributed to the fact that the catchment contains parts of Johannesburg, and many urbanizing areas. The average recorded yield for

Hartebeespoort Dam is 1,6 times the comparable non-urban yield for this region.

**Region 2**

This region is situated along the lower reaches of the Orange River. The region is arid and slow draining. Although a large quantity of sediment is available for transport, the transporting capacity of run-off is low. In this region the transporting mechanism, rather than the availability of sediment tends to be the limiting factor in determining yields.

Due to the fact that only a single yield has been recorded in this large region no meaningful analysis of yield values has been possible.

However, this is a region with relatively low water yields and it is unlikely that many reservoirs will be constructed in this area.

**Region 3**

Region 3 is situated within the catchment of the Vaal River. Reservoir sediment deposit survey data is available for 12 catchments and the recorded sediment yield values vary from 1 $t/km^2.a$ to 377 $t/km^2.a$.

Although this region is geologically somewhat diverse, the land use is relatively homogeneous and the region includes the country's main grain producing regions.

Sediment yield values do not converge towards a regional mean value, with increase in catchment size. This may be attributed to the fact that most of the smaller catchments for which data is available, are situated in the upper regions of the Vaal catchment, where sediment yields tend to be low. As the size of catchments increase, some areas with high sediment yield potential are added. This means that small catchments situated in the lower areas of the Vaal River catchment have to be treated with care, as their sediment yield potential may be higher than is reflected in the data.

**Region 4**

Region 4 is situated mainly in Natal, and includes Swaziland.

Sediment yield information is available for 20 reservoirs. Measured sediment yield values vary between 5 $t/km^2.a$ and 723 $t/km^2.a$.

The reservoirs, for which information is available, are not homogeneously distributed through the region. Most of the reservoirs are situated in the area between Durban and Lesotho within the catchments of the Mgeni and Tugela rivers. Little data is available in the vicinity of Swaziland.

The area is geologically varied. Land use varies from cattle farming in the Natal midlands, to sugar cane farming along the coast, with large reas of subsistence farming scattered throughout the region.

Despite this diversity, sediment yield values tend to converge to a regional mean value, with increase in catchment size.

Sugar cane production areas are not well represented in the available data. As these areas have high sediment yield potential, care has to be taken when evaluating sediment yield for areas in which sugar cane production is significant. Yields in excess of 1 000 $t/km^2.a$ are possible from such catchments.

**Region 5**

This region is situated in the Central Karoo and is geologically one of the more homogeneous regions. Sheep farming is the dominant land use.

Only 8 reservoirs with surveyed sediment records are available for the region. Measured sediment yield values vary from 4 $t/km^2.a$ to 169 $t/km^2.a$. Because of the limited data, a single value was estimated for each confidence limit. The limited number of points also precludes the possibility of detecting trends in sediment yields values with increase in catchment area.

**Region 6**

This region consists of the upper Orange and Caledon catchments down to the Verwoerd Dam including the south-eastern part of Lesotho. Some of the highest sediment yield areas in the country are situated in this region, mainly within the Caledon River catchment. Sediment surveys for 6 reservoirs are available. Some data obtained from suspended sediment yield measuring stations in Lesotho was also used. Measured sediment yield values range from 113 to 1 382 $t/km^2.a$.

The Verwoerd Dam catchment is the largest effective catchment in the country for which reservoir survey information is available and covers an area of 68 000 $km^2$. Once more, due to limited sediment yield data, only single confidence limit values were estimated without any indications of trends for increase in catchment size. The regional average is high and generally high sediment yields should be expected.

**Region 7**

Region 7 consists mainly of the basaltic regions of Lesotho situated along the upper Orange River (Senqu). Information of sediment yields in this region was obtained from a number of suspended sediment measuring stations with short records, mainly about 6 years.

Due to the fact that the basaltic regions have low sediment yields, the regional average yield is low as well. Some very high sediment yields occur in cases where the same soils that are present along the upper regions of the Caledon River, are included in certain catchments. This is the cause of the wide confidence limits for the region.

**Region 8**

Region 8 is situated in the Western Cape. Fruit farming is a main land use. Sediment surveys are available for 25 reservoirs. Observed sediment yields are between 1 $t/km^2.a$ and 310 $t/km^2.a$.

Catchment sizes in this region are relatively small. This results in relatively small total sediment yields for catchments, even though the unit yields for some of the catchments are relatively high.

The sediment yield values converge very clearly to a regional mean value. Some of the smaller catchments have exceptionally high values relative to the mean value.

At least some of these high values, notably that of the Wemmershoek Dam, can be ascribed to some extent to the influence of bush fires. Fires increase the resistance of the soils to water penetration and change the soil texture, resulting in increased surface run-off, higher flow velocities and increased sediment yields.

**Region 9**

Region 9 is situated in the South Eastern Cape and Transkei.

Sediment survey information for 18 reservoirs is available. Measured sediment yield values are between 4 $t/km^2.a$ and 881 $t/km^2.a$.

The region's data display the expected tendency of convergence of sediment yields values to a regional mean value, with increase in catchment size.

**Worked example**

The sediment yield for a hypothetical catchment of 200 $km^2$ in the Pretoria region has to be estimated.

According to the sediment yield regions map the catchment falls in region No 1. Say that 120 $km^2$ of the area consists of soil with medium sediment yield potential and 80 $km^2$ consists of soil with low yield potential.

From Table 5.5.1 the regional average standardized yield is determined as 49 $t/km^2.a$.

To determine a conservatively high estimate of this likely yield, the 95% confidence limit is used.

The 95% multiplying factor indicated on the graph (Region 1) for an area of 200 $km^2$ is 5,6 and therefore the standardized value to be used = regional mean x 5,6 = 274 $t/km^2.a$.

In Table 5.5.1, the factors $F_M$ for soil of medium yield potential and $F_L$, for soil of low yield potential are obtained. The values are 1 and 0.92 respectively.

To convert the standardized yield value to a weighed average yield value, substitute the values as follows:

$$Y_C = 274 \left[ 1 \left(\frac{120}{200}\right) + 0.92 \left(\frac{80}{200}\right) \right]$$

$$= 265 \text{ t/km}^2\text{.a}$$

A sensible check on this value is for instance the yield for the Roodeplaat Dam, which is also situated in the same area with a relatively small catchment. The measured value for Roodeplaat Dam is 105 $t/km^2.a$.

| Region | Standardized average Yield ($t/a.km^2$) | Sediment yield factors | | |
|---|---|---|---|---|
| | | $F_H$ (High) | $F_M$ (Medium) | $F_L$ (Low) |
| 1 | 49 | 2.23 | 1.00 | 0,92 |
| 2 | N/A | N/A | N/A | N/A |
| 3 | 82 | 1.87 | 1.00 | 0.35 |
| 4 | 155 | 1.44 | 1.00 | 0.18 |
| 5 | 30 | 2.69 | 1.00 | N/A |
| 6 | 335 | 1.00 | 1.00 | N/A |
| 7 | 203 | N/A | N/A | 1.00 |
| 8 | 35 | 1.00 | 1.00 | 0.23 |
| 9 | 185 | 1.00 | 1.00 | N/A |

TABLE 5.5.1: STANDARDIZED AVERAGE YIELD VALUES AND YIELD FACTORS

# TABLE 5.2.1: DAM LIST

| BRANCH | LOCATION NUMBER | DAM NAME | REGION | PERIOD | $V_W$ (END) ($10^6$ $m^3$) | $V_T$ ($10^6$ $m^3$) | $V_{50}$ ($10^6$ $m^3$) | ECA ($km^2$) | YIELD ($t/km^2.a$) | $V_T/V_W$ (%) | $V_W$ /MAR | $V_W$ /ECA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Limpopo | A210-02 | Hartebeespoort | 1 | 1923-1979 | 194.627 | 35.884 | 34.422 | 3633 | 256 | 15.6 | 1.19 | 53572 |
| Sterkstroom | A210-03 | Buffelspoort | 1 | 1935-1980 | 10.329 | 0.356 | 0.371 | 119 | 84 | 3.3 | 0.79 | 86794 |
| Hennops | A210-05 | Rietvlei | 1 | 1934-1977 | 12.197 | 0.674 | 0.714 | 479 | 40 | 5.2 | 0.79 | 25463 |
| Hex | A220-02 | Olifantsnek | 1 | 1928-1988 | 14.200 | 2.075 | 1.920 | 492 | 105 | 12.7 | 1.04 | 28862 |
| Koster | A220--3 | Koster | 1 | 1964-1980 | 12.176 | 0.215 | 0.375 | 280 | 36 | 1.7 | 1.13 | 43486 |
| Elands | A220-05 | Lindleyspoort | 1 | 1938-1980 | 14.417 | 2.018 | 2.159 | 705 | 83 | 12.3 | 0.73 | 20450 |
| Hex | A220-07 | Bospoort | 1 | 1953-1969 | 18.900 | 0.943 | 1.650 | 600 | 63 | 4.8 | 0.89 | 32143 |
| Pienaars | A230-01 | Roodeplaat | 1 | 1959-1980 | 43.691 | 1.797 | 2.667 | 684 | 105 | 4.0 | 1.53 | 63876 |
| Pienaars | A230-02 | Klipvoor | 1 | 1970-1987 | 42.578 | 1.443 | 2.429 | 2400 | 27 | 3.3 | 0.35 | 17741 |
| Apies | A230-08 | Bon Accord | 1 | 1925-1980 | 4.293 | 2.146 | 2.072 | 315 | 178 | 33.3 | - | 13629 |
| Bierspruit | A240-04 | Bierspruit | 1 | 1960-1980 | 3.498 | 0.634 | 0.967 | 1330 | 20 | 15.3 | 0.33 | 2630 |
| L/Marico | A300-02 | Kromellenboog | 1 | 1955-1983 | 9.375 | 2.309 | 2.953 | 606 | 132 | 19.8 | 0.68 | 15470 |
| L/Marico | A300-03 | Klein Maricoprt | 1 | 1934-1983 | 7.073 | 0.911 | 0.918 | 1180 | 21 | 11.4 | 0.62 | 5994 |
| G/Marico | A300-04 | Marico-Bosveld | 1 | 1933-1977 | 27.813 | 2.223 | 2.336 | 1219 | 52 | 7.4 | 0.96 | 22816 |
| Mogol | A400-02 | Hans Strydom | 1 | 1975-1988 | 149.000 | 0.869 | 1.762 | 4319 | 11 | 0.6 | 4.07 | 34499 |
| Sterk | A600-03 | Doorndraai | 1 | 1953-1979 | 47.255 | 1.582 | 2.098 | 579 | 98 | 3.2 | 2.06 | 81614 |
| Mogalakwena | A600-04 | Glen Alpine | 1 | 1967-1979 | 21.928 | 1.868 | 4.031 | 10713 | 10 | 7.8 | 0.16 | 2047 |
| Dorps | A600-05 | Combrink | 1 | 1964-1978 | 0.951 | 0.049 | 0.094 | 174 | 15 | 4.9 | 1.30 | 5465 |
| Sterk | A600-09 | Welgevonden | 1 | 1954-1977 | 0.679 | 0.026 | 0.037 | 166 | 6 | 3.7 | - | 4091 |
| Nzhelele | A800-01 | Nzhelele | 1 | 1948-1979 | 57.274 | 3.050 | 3.718 | 842 | 119 | 5.1 | - | 68021 |
| Nwandezi | A800-04 | Nwanedzi | 1 | 1963-1979 | 5.533 | 0.032 | 0.056 | 109 | 14 | 0.6 | - | 50762 |
| Luphephe | A800-05 | Luphephe | 1 | 1963-1979 | 15.019 | 0.115 | 0.201 | 150 | 36 | 0.8 | 0.53 | 100127 |
| Bronkhorst | B200-01 | Bronkhorstspruit | 1 | 1948-1983 | 58.902 | 1.954 | 2.257 | 1263 | 48 | 3.2 | 1.27 | 46637 |

| BRANCH | LOCATION NUMBER | DAM NAME | REGION | PERIOD | $V_W$ (END) ($10^6$ $m^3$) | $V_T$ ($10^6$ $m^3$) | $V_{50}$ ($10^6$ $m^3$) | ECA ($km^2$) | YIELD ($t/km^2.a$) | $V_T/V_W$ (%) | $V_W$ /MAR | $V_W$ /ECA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Elands | B310-01 | Rust de Winter | 1 | 1934-1977 | 28.483 | 1.303 | 1.382 | 1147 | 33 | 4.4 | 0.65 | 24832 |
| Olifants | B320-01 | Loskop | 1 | 1939-1977 | 348.100 | 11.238 | 12.533 | 5820 | 58 | 3.1 | 0.84 | 59811 |
| Watervals | B400-01 | Buffelskloof | 1 | 1972-1987 | 5.384 | 0.111 | 0.203 | 278 | 20 | 2.0 | 0.22 | 19367 |
| Klaserie | B700-09 | Jan Wassenaar | 1 | 1960-1979 | 5.779 | 0.470 | 0.739 | 165 | 121 | 7.5 | 0.34 | 35024 |
| G/Letaba | B800-02 | Ebenezer | 1 | 1959-1986 | 70.029 | 0.690 | 0.898 | 156 | 155 | 1.0 | 1.59 | 448903 |
| Politsi | B800-06 | Magoebaskloof | 1 | 1970-1986 | 4.915 | 0.102 | 0.179 | 64 | 76 | 2.0 | 0.13 | 76797 |
| Broederstroom | B800-17 | Dap Naude | 1 | 1961-1987 | 1.936 | 0.140 | 0.185 | 14 | 357 | 6.7 | - | 138307 |
| Ramadiepa | B800-21 | Hans Merensky | 1 | 1935-1987 | 1.234 | 0.082 | 0.081 | 88 | 25 | 6.2 | - | 14024 |
| Mooi | C230-01 | Klerkskraal | 3 | 1969-1982 | 8.249 | 0.423 | 0.858 | 1335 | 17 | 4.9 | 0.13 | 6179 |
| Mooi | C230-04 | Boskop | 3 | 1959-1981 | 20.854 | 0.400 | 0.579 | 1952 | 8 | 1.9 | 0.24 | 10684 |
| Loop | C230-06 | Klipdrift | 3 | 1918-1977 | 13.065 | 1.330 | 1.252 | 881 | 38 | 9.2 | 2.46 | 14830 |
| Schoonspruit | C240-01 | Rietspruit | 3 | 1955-1989 | 7.772 | 0.774 | 0.905 | 375 | 65 | 9.1 | - | 20725 |
| Schoonspruit | C240-05 | John Neser | 3 | 1915-1977 | 5.672 | 0.160 | 0.148 | 4200 | 1 | 2.7 | - | 1350 |
| Sand | C400-02 | Allemanskraal | 3 | 1960-1989 | 182.512 | 40.255 | 50.632 | 2655 | 373 | 8.1 | 2.35 | 68743 |
| G/Vet | C400-03 | Erfenis | 3 | 1959-1987 | 215.129 | 20.072 | 25.672 | 4000 | 173 | 8.5 | 1.57 | 53782 |
| Riet | C510-04 | Kalkfontein | 6 | 1938-1979 | 321.416 | 36.173 | 39.095 | 8647 | 122 | 10.1 | - | 37171 |
| Kaffir | C510-10 | Tierpoort | 6 | 1922-1979 | 34.343 | 4.042 | 3.853 | 922 | 113 | 10.5 | 1.72 | 37248 |
| Modder | C520-02 | Krugersdrift | 3 | 1970-1989 | 75.527 | 12.423 | 19.531 | 3355 | 157 | 14.1 | 0.81 | 22512 |
| Modder | C520-03 | Rustfontein | 6 | 1955-1981 | 72.654 | 4.738 | 6.284 | 600 | 283 | 6.1 | 2.88 | 121091 |
| Renoster | C700-02 | Koppies | 3 | 1911-1978 | 40,715 | 11.983 | 10.797 | 2147 | 136 | 22.7 | - | 18964 |
| Leeu | C700-03 | Roodepoort | 3 | 1896-1978 | 0.909 | 0.952 | 0.802 | 80 | 271 | 51.2 | 0.78 | 11356 |
| Leeu | C700-05 | Weltevrede | 3 | 1907-1978 | 1.842 | 1.072 | 0.880 | 63 | 377 | 36.8 | - | 29244 |
| Matjesvlei | C800-18 | Menin | 3 | 1922-1978 | 0.691 | 0.135 | 0.129 | 80 | 44 | 16.3 | 0.53 | 8638 |
| Leeu | D200-04 | Armenia | 3 | 1951-1987 | 14.167 | 0.544 | 0.621 | 529 | 32 | 3.7 | 0.60 | 26780 |

| BRANCH | LOCATION NUMBER | DAM NAME | REGION | PERIOD | $V_W$ (END) ($10^6$ $m^3$) | $V_T$ ($10^6$ $m^3$) | $V_{50}$ ($10^6$ $m^3$) | ECA ($km^2$) | YIELD ($t/km^2.a$) | $V_T/V_W$ (%) | $V_W$ /MAR | $V_W$ /ECA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Blaasbalk | D200-17 | Poortjie | 6 | 1925-1981 | 5.408 | 1.993 | 1.912 | 450 | 115 | 26.9 | - | 12018 |
| Oranje | D350-02 | Hendrik Verwoerd | 6 | 1971-1979 | 5673.778 | 274.989 | 884.691 | 67845 | 352 | 4.6 | 0.66 | 83629 |
| Bethulie | D350-04 | Bethulie | 6 | 1921-1979 | 1.969 | 4.542 | 4.302 | 255 | 455 | 69.8 | 0.34 | 7720 |
| Swartbas | D420-01 | Leeubos | 2 | 1949-1983 | 0.998 | 0.129 | 0.151 | 259 | 16 | 11.4 | 0.72 | 3854 |
| Van Wyksvlei | D540-01 | Van Wyksvlei | 5 | 1884-1979 | 143.081 | 2.248 | 1.300 | 1339 | 26 | 1.5 | - | 106857 |
| Ongers | D600-01 | Smartt | 5 | 1912-1980 | 100.287 | 2.217 | 1.987 | 13114 | 4 | 2.2 | 2.48 | 7647 |
| Dorp | D600-06 | Victoria-Wes | 5 | 1924-1954 | 3.660 | 0.440 | 0.545 | 280 | 53 | 10.7 | - | 13071 |
| Olifants | E100-02 | Clanwilliam | 8 | 1935-1980 | 124.092 | 9.715 | 10.117 | 2033 | 134 | 7.3 | 0.32 | 61039 |
| Olifants | E100-04 | Bulshoek | 8 | 1922-1980 | 6.298 | 0.486 | 0.460 | 736 | 17 | 7.2 | 0.01 | 8557 |
| Wemmershoek | G100-13 | Wemmershoek | 8 | 1957-1984 | 58.797 | 1.102 | 1.434 | 125 | 310 | 1.8 | - | 470373 |
| Stettynskloof | H100-18 | Stettynskloof | 8 | 1954-1984 | 15.543 | 0.088 | 0.109 | 55 | 54 | 0.6 | 0.33 | 282600 |
| Koekedouw | H101-51 | Ceres | 8 | 1953-1981 | 0.347 | 0.018 | 0.023 | 50 | 12 | 4.9 | - | 6968 |
| Sanddrif | H200-07 | Roode Elsburg | 8 | 1968-1983 | 7.744 | 0.373 | 0.682 | 59 | 202 | 4.6 | 0.39 | 131247 |
| Groot | H300-01 | Poortjieskloof | 8 | 1957-1979 | 9.960 | 0.247 | 0.358 | 94 | 103 | 2.4 | 1.38 | 105952 |
| Keisies | H300-02 | Pietersfontein | 8 | 1968-1981 | 2.062 | 0.570 | 1.155 | 116 | 269 | 21.7 | 4.48 | 17774 |
| Nuy | H400-02 | Keerom | 8 | 1954-1981 | 7.398 | 0.946 | 1.232 | 378 | 88 | 11.3 | 1.03 | 19571 |
| Konings | H400-06 | Klipberg | 8 | 1964-1983 | 1.996 | 0.002 | 0.002 | 54 | 1 | 0.1 | 1.80 | 36967 |
| Hoeks | H400-10 | Moordkuil | 8 | 1950-1985 | 1.520 | 0.048 | 0.056 | 176 | 9 | 3.1 | - | 8634 |
| Buffeljags | H700-02 | Buffeljags | 8 | 1966-1983 | 5.736 | 0.090 | 0.152 | 601 | 7 | 1.5 | 0.05 | 9543 |
| Duiwenhoks | H800-03 | Duiwenhoks | 8 | 1965-1979 | 6.406 | 0.058 | 0.112 | 148 | 20 | 0.9 | 0.22 | 43283 |
| Korinte | H900-03 | Korentepoort | 8 | 1965-1983 | 8.296 | 0.028 | 0.045 | 37 | 33 | 0.3 | - | 224224 |
| Buffels | J110-01 | Floriskraal | 6 | 1957-1981 | 51.951 | 15.486 | 25.000 | 4001 | 169 | 23.0 | 2.49 | 12985 |
| Brak | J120-02 | Bellair | 8 | 1920-1981 | 10.077 | 0.933 | 0.700 | 558 | 34 | 8.5 | 0.45 | 18059 |
| Prins | J120-04 | Prinsrivier | 8 | 1916-1981 | 1.262 | 4.189 | 3.813 | 757 | 136 | 76.9 | 0.37 | 1667 |

| BRANCH | LOCATION NUMBER | DAM NAME | REGION | PERIOD | $V_W$ (END) ($10^6$ $m^3$) | $V_T$ ($10^6$ $m^3$) | $V_{50}$ ($10^6$ $m^3$) | ECA ($km^2$) | YIELD ($t/km^2.a$) | $V_T/V_W$ (%) | $V_W$ /MAR | $V_W$ /ECA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Gamka | J210-01 | Gamka | 5 | 1955-1980 | 2,165 | 0.187 | 0.253 | 98 | 70 | 7.9 | 0.50 | 22092 |
| Leeu | J220-01 | Leeu Gamka | 5 | 1959-1981 | 14.154 | 7.478 | 10.818 | 2088 | 140 | 34.6 | 0.49 | 6779 |
| Cordiers | J230-01 | Oukloof | 5 | 1929-1984 | 4.222 | 0.293 | 0.283 | 141 | 54 | 6.5 | 1.13 | 29945 |
| Gamka | J250-01 | Gamkapoort | 5 | 1969-1981 | 43.836 | 10.122 | 21.849 | 17076 | 35 | 18.8 | 1.09 | 2567 |
| Nels | J250-02 | Calitzdorp | 8 | 1917-1981 | 4.817 | 0.997 | 0.850 | 170 | 135 | 17.2 | 0.67 | 28334 |
| Olifants | J330-01 | Stompdrift | 8 | 1965-1981 | 55.316 | 6.438 | 11.265 | 5235 | 58 | 10.4 | 2.27 | 10567 |
| Kammanassie | J340-02 | Kammanassie | 8 | 1923-1981 | 35.855 | 3.584 | 3.000 | 1505 | 54 | 9.1 | 0.98 | 23824 |
| L/Le Roux | J350-04 | Raubenheimer | 8 | 1973-1984 | 9.203 | 0.005 | 0.011 | 43 | 7 | 0.1 | 0.52 | 150875 |
| L/Le Roux | J350-05 | Melville | 8 | 1945-1984 | 0.466 | 0.001 | 0.001 | 18 | 1 | 0.2 | - | 25900 |
| Hartenbos | K100-02 | Hartebeeskuil | 8 | 1969-1981 | 7.162 | 0.011 | 0.024 | 100 | 7 | 0.2 | 4.07 | 71615 |
| G/Brak | K100-06 | Ernest Robertson | 8 | 1955-1985 | 0.419 | 0.004 | 0.004 | 10 | 12 | 0.9 | 0.11 | 41940 |
| Krom | K900-01 | Churchill | 8 | 1943-1987 | 35.678 | 0.122 | 0.128 | 357 | 10 | 0.3 | - | 99939 |
| Koega | L820-1 | Paul Sauer | 8 | 1969-1986 | 128.490 | 1.515 | 2.549 | 3887 | 18 | 1.2 | 0.64 | 33056 |
| Loerie | L900-01 | Loerie | 8 | 1971-1984 | 3.362 | 0.752 | 1.524 | 147 | 280 | 18.3 | 0.08 | 22869 |
| Sondags | N120-01 | Van Ryneveldspas | 9 | 1925-1978 | 47.426 | 31.397 | 27.500 | 3544 | 210 | 39.8 | 1.40 | 13382 |
| Sondags | M230-01 | Lake Mentz | 9 | 1922-1978 | 191.758 | 135.670 | 130.140 | 12987 | 271 | 41.4 | 1.09 | 14765 |
| Nuwejaars | P100-01 | Nuwejaars | 9 | 1958-1981 | 4.622 | 0.057 | 0.081 | 531 | 4 | 1.2 | - | 8704 |
| G/Brak | Q130-01 | Grassridge | 9 | 1924-1984 | 49.576 | 41.252 | 38.610 | 4325 | 241 | 45.4 | 0.55 | 11463 |
| Tarka | Q410-01 | Kommandodrif | 9 | 1956-1985 | 58.800 | 14.663 | 21.000 | 3623 | 157 | 20.0 | 1.68 | 16230 |
| Tarka | Q440-01 | Lake Arthur | 9 | 1924-1985 | 29.255 | 68.059 | 63.331 | 3450 | 496 | 69.9 | 0.46 | 8480 |
| G/Vis | Q500-01 | Elandsdrift | 9 | 1973-1981 | 9.720 | 2.459 | 7.912 | 8042 | 27 | 20.2 | - | 1209 |
| Kat | Q940-01 | Katrivier | 9 | 1969-1988 | 24.873 | 1.887 | 2.966 | 258 | 310 | 7.6 | 1.18 | 96319 |
| Buffels | R200-02 | Laing | 9 | 1950-1981 | 21.035 | 1.708 | 2.400 | 862 | 75 | 7.5 | 0.34 | 24403 |
| Buffels | R200-05 | Bridle Drift | 9 | 1968-1981 | 73.509 | 5.146 | 10.430 | 375 | 751 | 6.5 | 0.71 | 196023 |

| BRANCH | LOCATION NUMBER | DAM NAME | REGION | PERIOD | $V_W$ (END) ($10^6$ $m^3$) | $V_T$ ($10^6$ $m^3$) | $V_{50}$ ($10^6$ $m^3$) | ECA ($km^2$) | YIELD ($t/km^2.a$) | $V_T/V_W$ (%) | $V_W$ /MAR | $V_W$ /ECA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Buffels | R200-07 | Maden | 9 | 1909-1981 | 0.266 | 0.053 | 0.047 | 30 | 42 | 16.8 | - | 8850 |
| Nahoon | R300-01 | Nahoon | 9 | 1964-1981 | 20.759 | 1.201 | 2.021 | 474 | 115 | 5.5 | 0.52 | 43795 |
| Wit Kei | S100-01 | Xonxa | 9 | 1974-1986 | 135.080 | 22.486 | 48.536 | 1487 | 881 | 14.3 | - | 90841 |
| Doring | S200-01 | Indwe | 9 | 1969-1984 | 23.444 | 3.864 | 7.061 | 295 | 646 | 14.1 | - | 79471 |
| Klipplaat | S300-06 | Waterdown | 9 | 1958-1988 | 38.200 | 0.213 | 0.264 | 603 | 12 | 0.6 | 0.72 | 63350 |
| Tsomo | S500-01 | Ncora | 9 | 1976-1988 | 154.076 | 8.193 | 17.686 | 1772 | 269 | 5.0 | - | 86951 |
| Gubu | S600-04 | Gubu | 9 | 1970-1981 | 9.254 | 0.059 | 0.137 | 23 | 161 | 0.6 | 2.16 | 402330 |
| Mtata | T201-03 | Mtata | 9 | 1977-1987 | 257.097 | 1.129 | 2.859 | 868 | 89 | 0.4 | - | 296195 |
| Umgeni | U200-01 | Albert Falls | 4 | 1974-1983 | 289.167 | 0.295 | 0.832 | 716 | 31 | 0.1 | 1.14 | 403864 |
| Umgeni | U200-03 | Midmar | 4 | 1965-1983 | 177.114 | 0.204 | 0.330 | 928 | 10 | 0.1 | 1.01 | 190855 |
| Umzinduzi | U200-09 | Henley | 4 | 1942-1987 | 5.407 | 0.355 | 0.370 | 238 | 42 | 6.2 | - | 22717 |
| Mdloti | U300-01 | Hazelmere | 4 | 1975-1987 | 19.223 | 4.679 | 10.099 | 377 | 723 | 19.6 | 0.33 | 50989 |
| Mlazi | U600-03 | Shongweni | 4 | 1927-1987 | 5.208 | 6.853 | 6.414 | 750 | 231 | 56.8 | - | 6945 |
| Tugela | V100-01 | Spioenkop | 4 | 1972-1986 | 279.628 | 6.367 | 12.214 | 774 | 426 | 2.2 | 0.50 | 361276 |
| Mnyamvubu | V200-02 | Craigie Burn | 4 | 1963-1983 | 23.446 | 0.108 | 0.164 | 152 | 29 | 0.5 | 0.88 | 154253 |
| Ngagane | V300-04 | Chelmsford | 4 | 1961-1983 | 198.438 | 3.400 | 4.919 | 830 | 160 | 1.7 | 1.17 | 239081 |
| Boesmans | V700-01 | Wagendrift | 4 | 1963-1983 | 58.362 | 1.639 | 2.500 | 744 | 91 | 2.7 | 0.28 | 78444 |
| Hluhluwe | W300-03 | Hluhluwe | 4 | 1964-1985 | 28.775 | 2.517 | 3.736 | 734 | 137 | 8.0 | 0.72 | 39202 |
| Pongola | W440-01 | Pongolapoort | 4 | 1973-1984 | 2445.258 | 55.656 | 129.262 | 7831 | 446 | 2.2 | 4.54 | 312254 |
| Mpapa | W530-03 | Jericho | 4 | 1966-1983 | 59.834 | 1.011 | 1.701 | 218 | 211 | 1.7 | 1.32 | 274470 |
| Usutu | W540-01 | Westoe | 4 | 1968-1980 | 61.011 | 0.044 | 0.096 | 531 | 5 | 0.1 | 1.35 | 114898 |
| Komati | X100-09 | Nooitgedacht | 4 | 1962-1983 | 78.824 | 1.162 | 1.724 | 1569 | 30 | 1.5 | 1.39 | 50238 |
| Wit | X200-04 | Primkop | 4 | 1970-1987 | 2.017 | 0.191 | 0.322 | 158 | 55 | 8.7 | 0.08 | 12763 |
| Wit | X200-13 | Longmere | 4 | 1940-1979 | 4.347 | 0.227 | 0.250 | 27 | 250 | 5.0 | 0.26 | 161000 |

| BRANCH | LOCATION NUMBER | DAM NAME | REGION | PERIOD | $V_W$ (END) ($10^6$ $m^3$) | $V_T$ ($10^6$ $m^3$) | $V_{50}$ ($10^6$ $m^3$) | ECA ($km^2$) | YIELD ($t/km^2.a$) | $V_T/V_W$ (%) | $V_W$ /MAR | $V_W$ /ECA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sand | X200-20 | Witteklip | 4 | 1969-1979 | 12.972 | 0.150 | 0.379 | 64 | 160 | 1.1 | 0.78 | 202691 |
| Wit | X200-23 | Klipkopjes | 4 | 1960-1979 | 11.866 | 0.430 | 0.676 | 78 | 234 | 3.5 | - | 152131 |
| Witwaters | X300-02 | Da Gama | 4 | 1971-1979 | 13.653 | 0.404 | 1.300 | 62 | 566 | 2.9 | 1.10 | 220202 |
| Klip | - | Windsor | 4 | - | - | - | 1.087 | 2329 | 126 | - | - | - |
| Mgeni | - | Camperdown | 4 | 1901-1923 | 1.364 | 0.909 | 1.170 | 376 | 84 | 0.67 | - | 3628 |

REGION = SEDIMENT YIELD REGION (SECT 3.7)

$V_W$(END) = VOLUME OF RESERVOIR AT MOST RECENT SURVEY

$V_T$ = VOLUME OF SEDIMENT DEPOSIT

$V_{50}$ = EQUIVALENT 50 YEAR SEDIMENT DEPOSIT VALUE

ECA = EFFECTIVE CATCHMENT AREA

YIELD = ANNUAL YIELD PER UNIT AREA (MASS)

MAR = MEAN ANNUAL RUN-OFF

| STATION | RIVER | ID | REG | TOTAL AREA | PERIOD 1929 - 1934 | 1934 - 1943 | 1943 - 1952 | 1952 - 1960 | 1960 - 1969 |
|---|---|---|---|---|---|---|---|---|---|
| Oranjedraai | Orange | 6 | 6 | 24876 | - | - | - | - | 402 |
| Aliwal-North | Orange | 5 | 6 | 37202 | 414 | 366 | 470 | 530 | 462 |
| Jammersdrift | Caled. | 9 | 6 | 13320 | 923 | 871 | - | - | - |
| Bethulie | Orange | 23 | 6 | 65151 | 646 | 536 | 657 | 669 | 560 |
| Oranjerivierbrug | Orange | 17 | 5 | 94464 | 630 | 493 | 562 | - | - |
| Barrage | Vaal | 22 | 3 | 45882 | 85 | - | - | - | - |
| Paardeberg | Modder | 15 | 3 | 14791 | - | - | 311 | - | - |
| Leeuwkraal | Riet | 16 | 3 | 11000 | 100 | - | - | - | - |
| Prieska/ Upington | | 18/20 | 3 | 329582 | 311 | 196 | 183 | 161 | 119 |

**TABLE 5.2.2(a): AVERAGE SEDIMENT TRANSPORT YIELDS AT VARIOUS MEASURING STATIONS (ORANGE RIVER SYSTEM) ($t/km^2.a$) [ROOSEBOOM AND MAAS - 1974]**

| STATION | RIVER | ID | REG* | AREA $km^2$ | YIELD $t/km^2.a$ | PERIOD |
|---|---|---|---|---|---|---|
| Colenso | Tugela | 19 | 4 | 4203 | 571 | 1950 - 1958 |
| Intulembi | Pongola | 14 | 4 | 7147 | 133 | 1928 - 1945 |
| Burghersdorp | Stormberg | - | 6 | 2370 | 762 | 1935 - 1948 |
| Standerton | Vaal | - | 3 | 8254 | 193 | 1929 - 1940 |
| Vetrivierbrug | Vet | 21 | 3 | 5504 | 279 | 1935 - 1947 |
| Schweizer Reneke | Hartz | - | 3 | 9251 | 7 | 1934 - 1956 |
| Sannaspos | Modder | 28 | 3 | 1650 | 304 | 1935 - 1943 |
| Jansenville | Sondags | 27 | 9 | 11560 | 136 | 1930 - 1948 |
| Buffelsfontein | L/Fish | 26 | 9 | 995 | 589 | 1931 - 1939 |
| Hougham Abramson | G/Fish | 30 | 9 | 18436 | 209 | 1930 - 1940 |
| Upsher | Kat | 25 | 9 | 554 | 499 | 1931 - 1948 |

* REG = SEDIMENT YIELD REGION (SECTION 3.7)

**TABLE 5.2.2(b): OTHER YIELD DATA DERIVED FROM STREAM SAMPLING**

| LOC. No. | STATION | RIVER | ID | REG* | AREA ($km^2$) | YIELD ($t/km^2.a$) | PERIOD |
|---|---|---|---|---|---|---|---|
| SG3 | Seaka | Senqu | 8 | 6 | 8975 | 295 | 1976-1982 |
| SG4 | Whitehill | Senqu | 1 | 7 | 2950 | 329 | 1976-1982 |
| SG45 | Ha Lejone | Malibamatso | 4 | 7 | 1157 | 9 | 1976-1982 |
| SG5 | Koma-Koma | Senqu | 2 | 7 | 2198 | 89 | 1976-1982 |
| SG8 | Paray | Malibamatso | 3 | 7 | 1018 | 175 | 1976-1982 |
| CG24 | Masianokeng | S. Phutiatsana | 10 | 6 | 945 | 1382 | 1976-1982 |
| CG34 | Mapoteng | N. Phutiatsana | 11 | 7 | 386 | 2050 | 1976-1982 |
| CG38 | Mashili | Caledon | 12 | 6 | 1348 | 832 | 1976-1982 |
| CG39 | Mohlokagala | Caledon | 13 | 6 | 3312 | 1055 | 1976-1982 |

*REG = SEDIMENT YIELD REGION (SECTION 3.7)

**TABLE 5.2.2(c): LESOTHO SEDIMENT YIELD VALUES (MAKHOALIBE - 1984)**

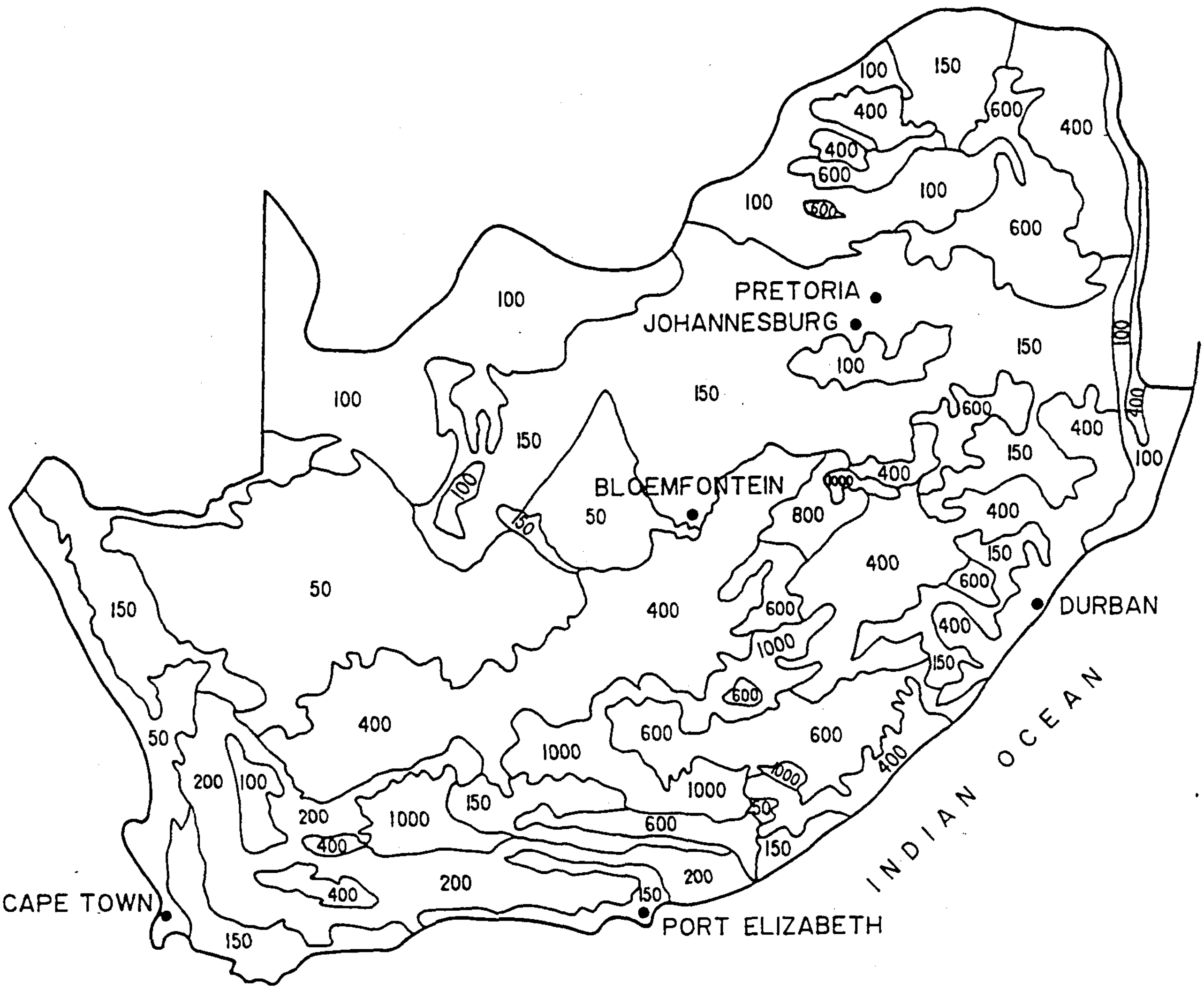
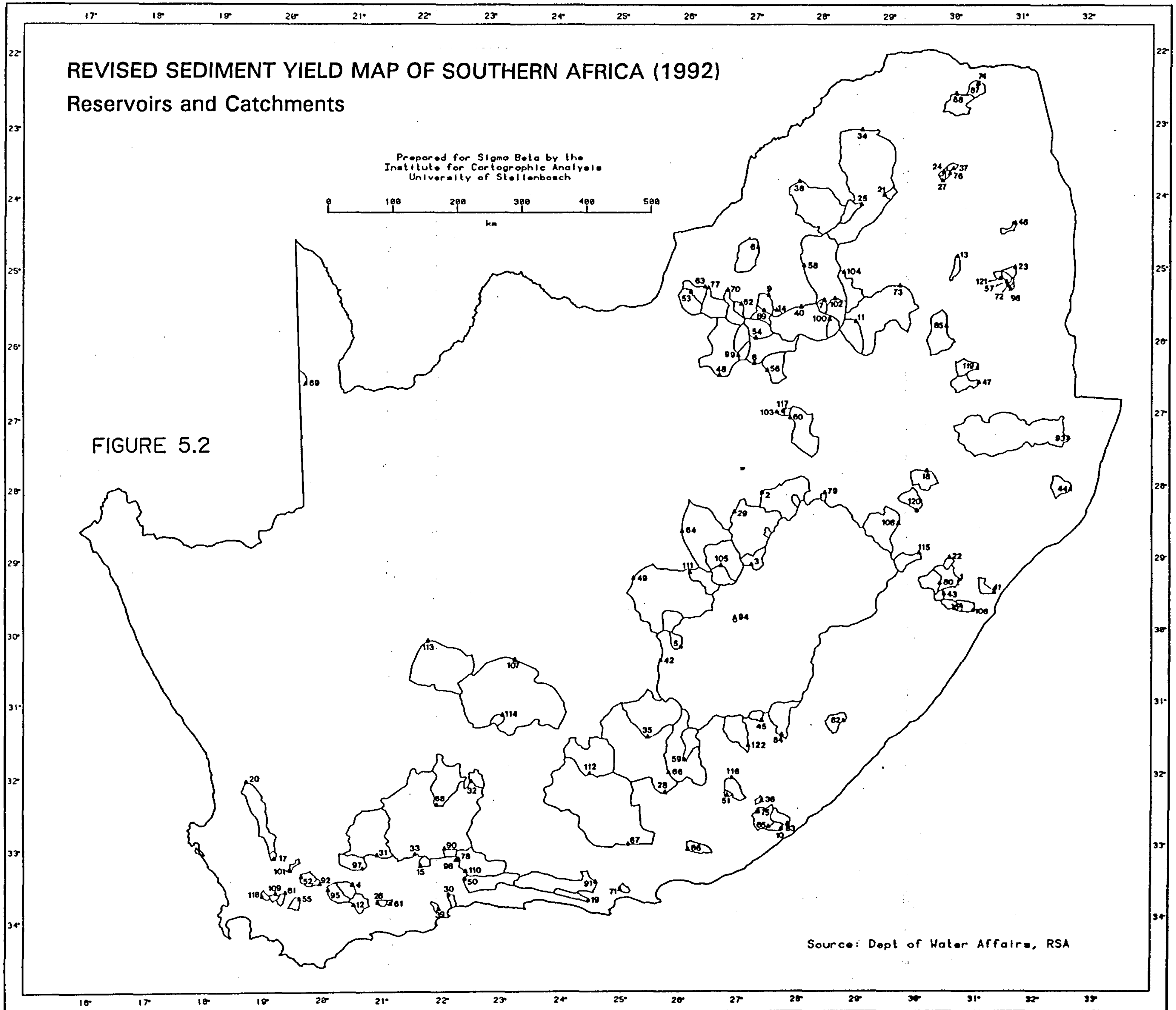



FIGURE 5.1 : THE 1978 SEDIMENT YIELD MAP FOR SOUTHERN AFRICA : INDICATING MAXIMUM OBSERVED YIELD VALUES




**Reservoir Names**

| | |
|---|---|
| 1 | Albert Falls |
| 2 | Allemanskraal |
| 3 | Armenia |
| 4 | Bellair |
| 5 | Bethulie |
| 6 | Bierspruit |
| 7 | Bon Accord |
| 8 | Boskop |
| 9 | Bospoort |
| 10 | Bridle Drift |
| 11 | Bronkhorstspruit |
| 12 | Buffeljags |
| 13 | Buffelskloof |
| 14 | Buffelspoort |
| 15 | Calitzdorp |
| 16 | Camperdown |
| 17 | Ceres |
| 18 | Chelmsford |
| 19 | Churchill |
| 20 | Clanwilliam |
| 21 | Combrink |
| 22 | Craigie Burn |
| 23 | Da Gama |
| 24 | Dap Naude |
| 25 | Doorndraai |
| 26 | Duivenhoks |
| 27 | Ebenezer |
| 28 | Elandsdrift |
| 29 | Erfenis |
| 30 | Ernest Robertson |
| 31 | Floriskraal |
| 32 | Gamka |
| 33 | Gamkapoort |
| 34 | Glen Alpine |
| 35 | Grassridge |
| 36 | Gubu |
| 37 | Hans Merensky |
| 38 | Hans Strydom |
| 39 | Hartebeeskuil |
| 40 | Hartebeespoort |
| 41 | Hazelmere |
| 42 | Hendrik Verwoerd |
| 43 | Henley |
| 44 | Hluhluwe |
| 45 | Indwe |
| 46 | Jan Wassenaar |
| 47 | Jericho |
| 48 | Johan Neser |
| 49 | Kalkfontein |
| 50 | Kammanassie |
| 51 | Katrivier |
| 52 | Keerom |
| 53 | Klein-Maricoprt |
| 54 | Klerkskraal |
| 55 | Klipberg |
| 56 | Klipdrift |
| 57 | Klipkopjes |
| 58 | Klipvoor |
| 59 | Kommandodrif |
| 60 | Koppies |
| 61 | Korentepoort |
| 62 | Koster |
| 63 | Krommellenboog |
| 64 | Krugersdrift |
| 65 | Laing |
| 66 | Lake Arthur |
| 67 | Lake Mentz |
| 68 | Leeu Gamka |
| 69 | Leeubos |
| 70 | Lindleyspoort |
| 71 | Loerie |
| 72 | Longmere |
| 73 | Loskop |
| 74 | Luphephe |
| 75 | Maden |
| 76 | Magoebaskloof |
| 77 | Marico-Bosveld |
| 78 | Melville |
| 79 | Menin |
| 80 | Midmar |
| 81 | Moordkuil |
| 82 | Mtata |
| 83 | Nahoon |
| 84 | Ncora |
| 85 | Nooitgedacht |
| 86 | Nuwejaars |
| 87 | Nwanedzi |
| 88 | Nzhelele |
| 89 | Olifantsnek |
| 90 | Oukloof |
| 91 | Paul Sauer |
| 92 | Pietersfontein |
| 93 | Pongolapoort |
| 94 | Poortjie |
| 95 | Poortjieskloof |
| 96 | Primkop |
| 97 | Prinsrivier |
| 98 | Raubenheimer |
| 99 | Rietspruit |
| 100 | Rietvlei |
| 101 | Roode Elsberg |
| 102 | Roodeplaat |
| 103 | Roodepoort |
| 104 | Rust de Winter |
| 105 | Rustfontein |
| 106 | Shongweni |
| 107 | Smartt |
| 108 | Spioenkop |
| 109 | Stettynskloof |
| 110 | Stompdrift |
| 111 | Tierpoort |
| 112 | Van Ryneveldspas |
| 113 | Van Wyksvlei |
| 114 | Victoria-Wes |
| 115 | Wagendrift |
| 116 | Waterdown |
| 117 | Weltevrede |
| 118 | Wemmershoek |
| 119 | Westoe |
| 120 | Windsor |
| 121 | Witteklip |
| 122 | Xonxa |

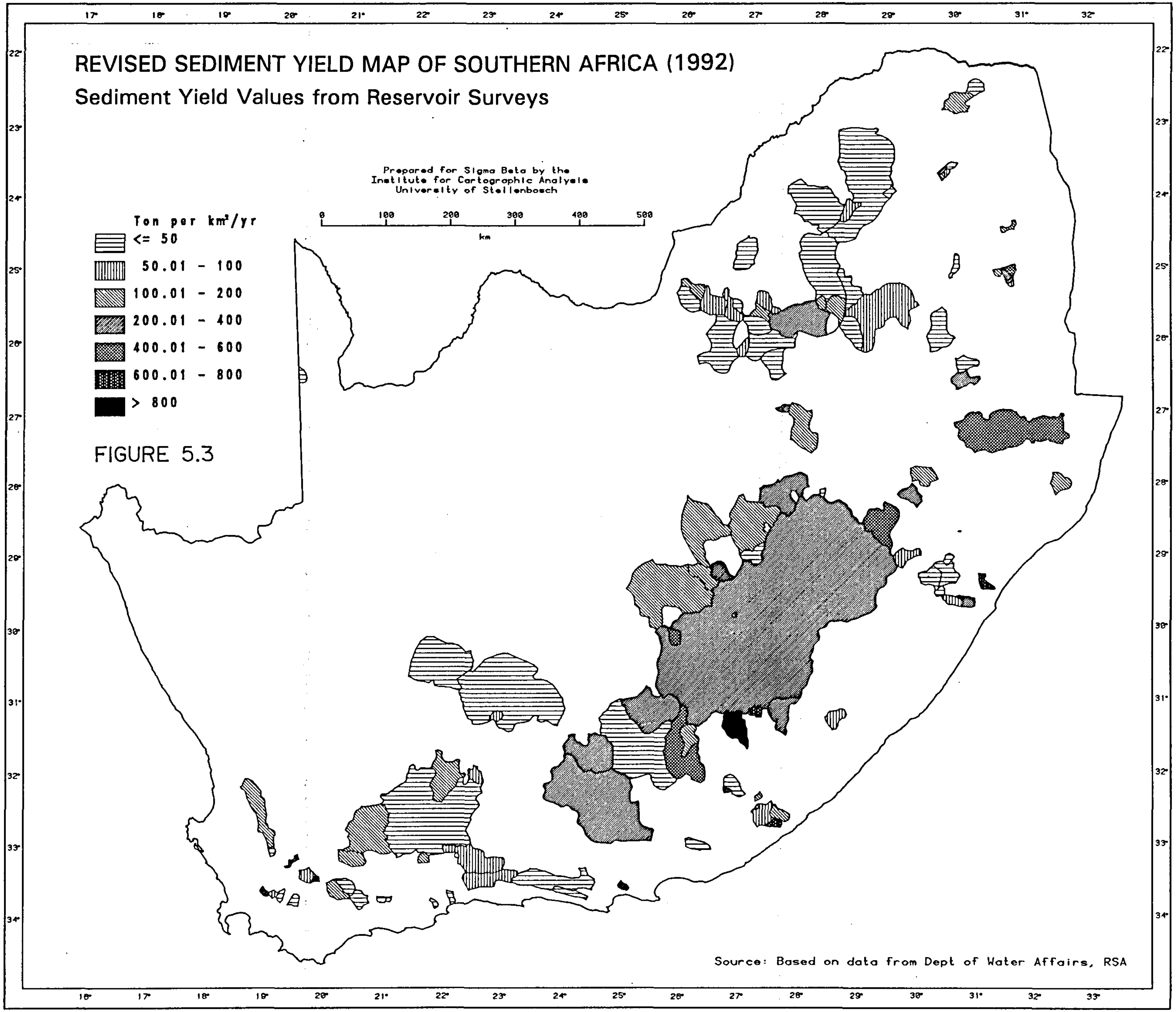
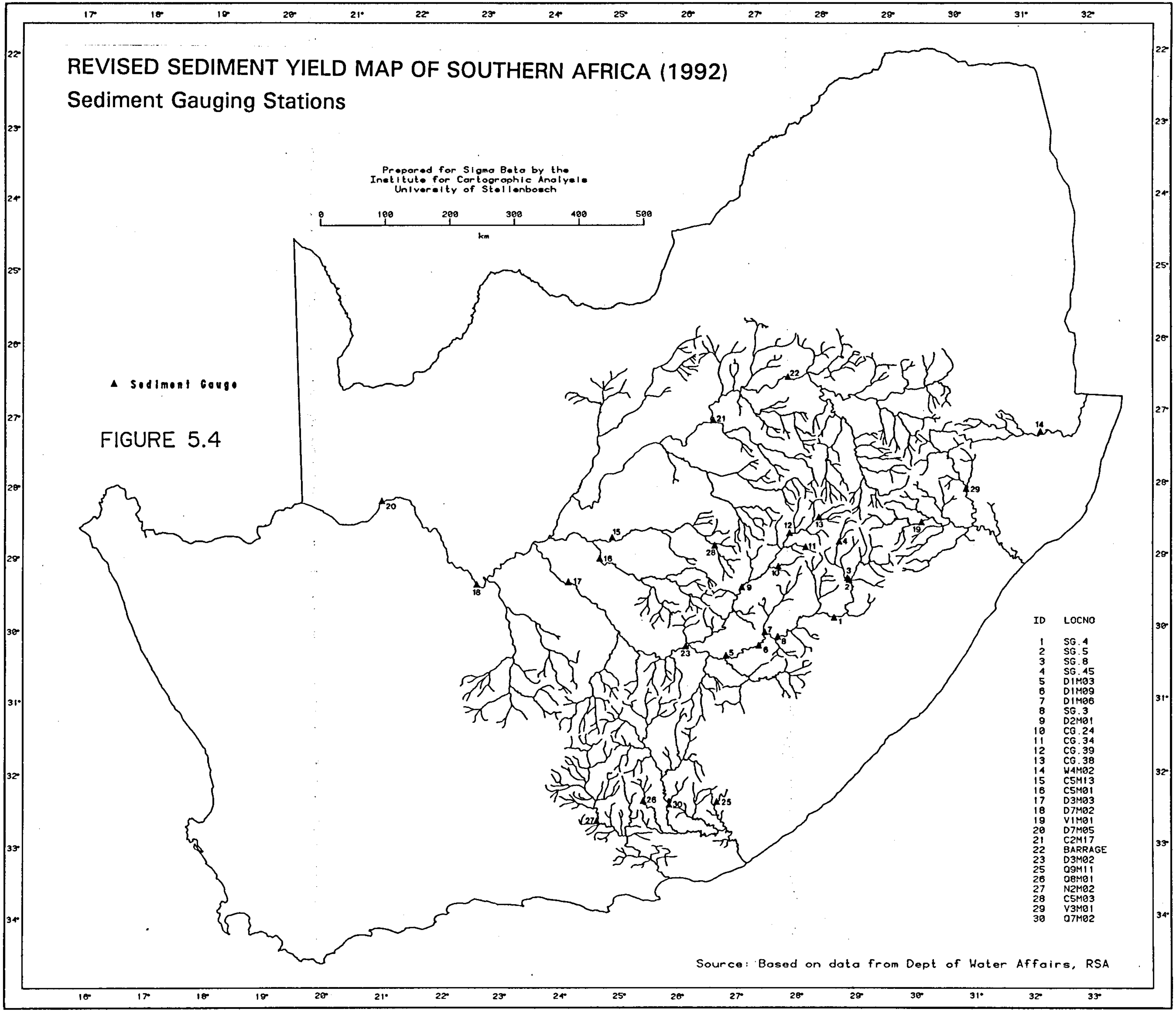
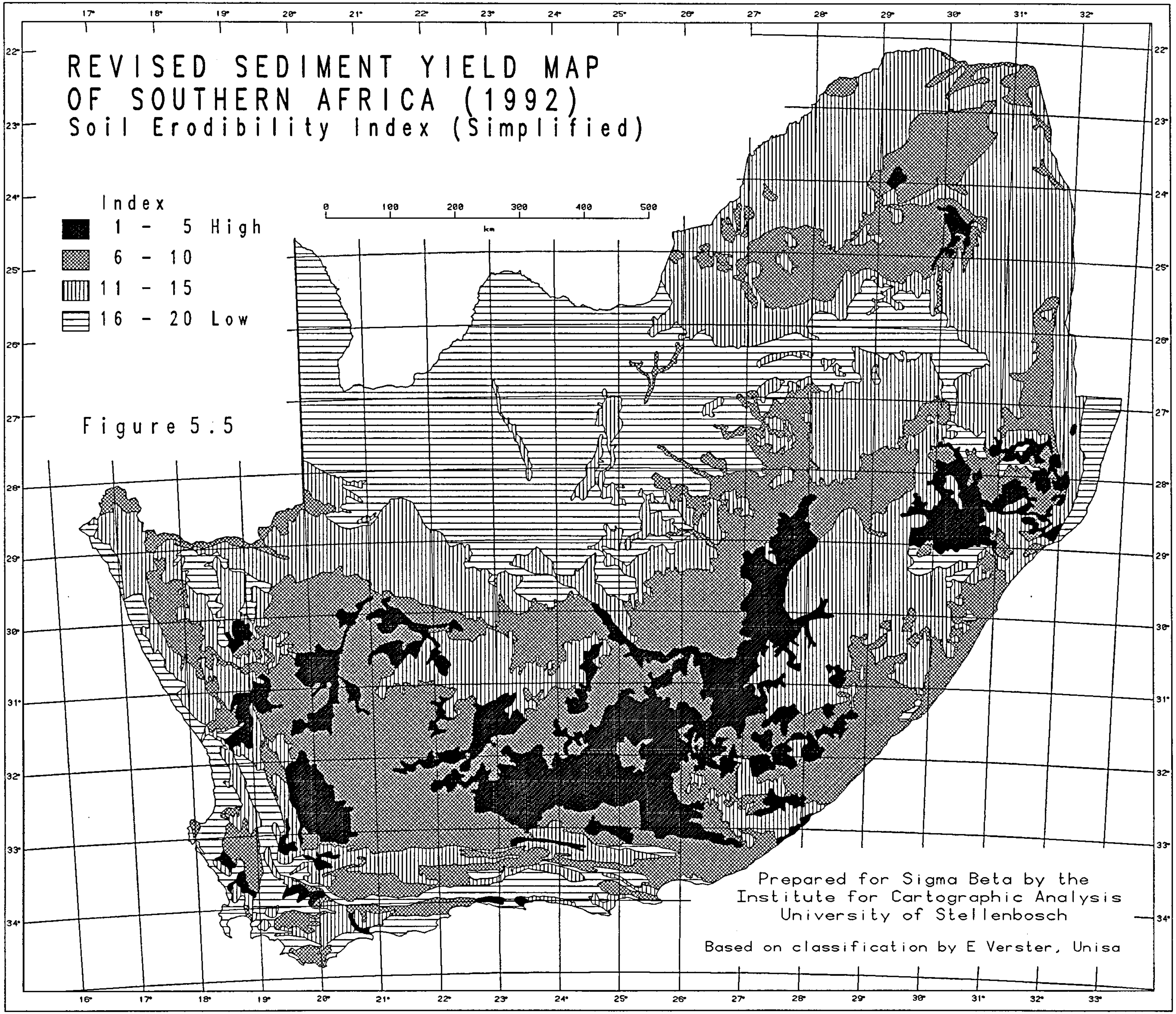

REVISED SEDIMENT YIELD MAP OF SOUTHERN AFRICA (1992)
Sediment Yield Values from Reservoir Surveys
Prepared for Sigma Beta by the Institute for Cartographic Analysis University of Stellenbosch
0 100 200 300 400 500
km
Ton per km²/yr
<= 50
50.01 - 100
100.01 - 200
200.01 - 400
400.01 - 600
600.01 - 800
> 800
Source: Based on data from Dept of Water Affairs, RSA

FIGURE 5.3



REVISED SEDIMENT YIELD MAP OF SOUTHERN AFRICA (1992)
Sediment Gauging Stations
Prepared for Sigma Beta by the
Institute for Cartographic Analysis
University of Stellenbosch
0 100 200 300 400 500
km
▲ Sediment Gauge
FIGURE 5.4
ID LOCNO
1 SG.4
2 SG.5
3 SG.8
4 SG.45
5 D1M03
6 D1M09
7 D1M06
8 SG.3
9 D2M01
10 CG.24
11 CG.34
12 CG.39
13 CG.38
14 W4M02
15 C5M13
16 C5M01
17 D3M03
18 D7M02
19 V1M01
20 D7M05
21 C2M17
22 BARRAGE
23 D3M02
25 Q9M11
26 Q8M01
27 N2M02
28 C5M03
29 V3M01
30 Q7M02
Source: Based on data from Dept of Water Affairs, RSA



REVISED SEDIMENT YIELD MAP
OF SOUTHERN AFRICA (1992)
Soil Erodibility Index (Simplified)
Index
1 - 5 High
6 - 10
11 - 15
16 - 20 Low
0 100 200 300 400 500
km
Figure 5.5
Prepared for Sigma Beta by the
Institute for Cartographic Analysis
University of Stellenbosch
Based on classification by E Verster, Unisa

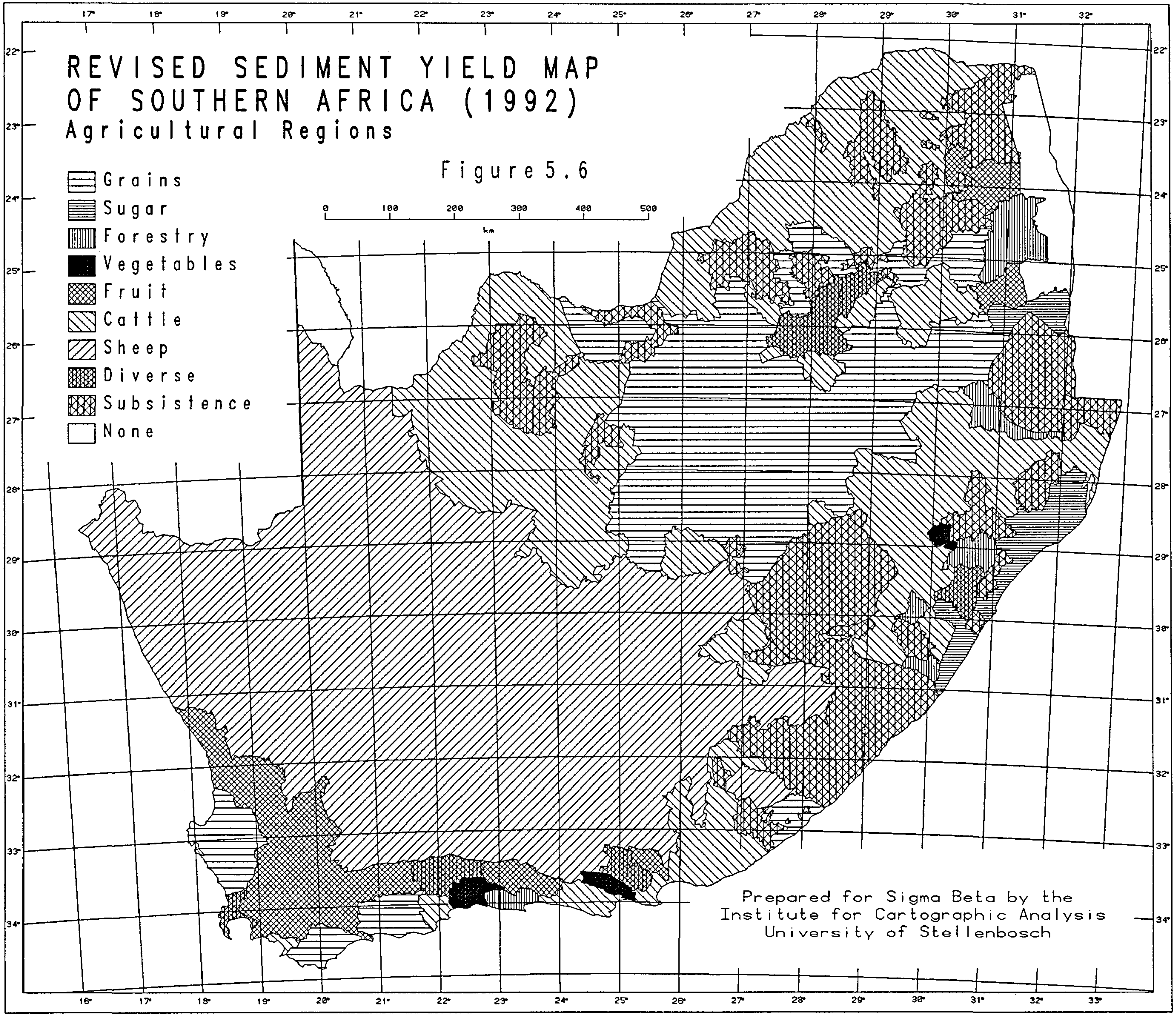
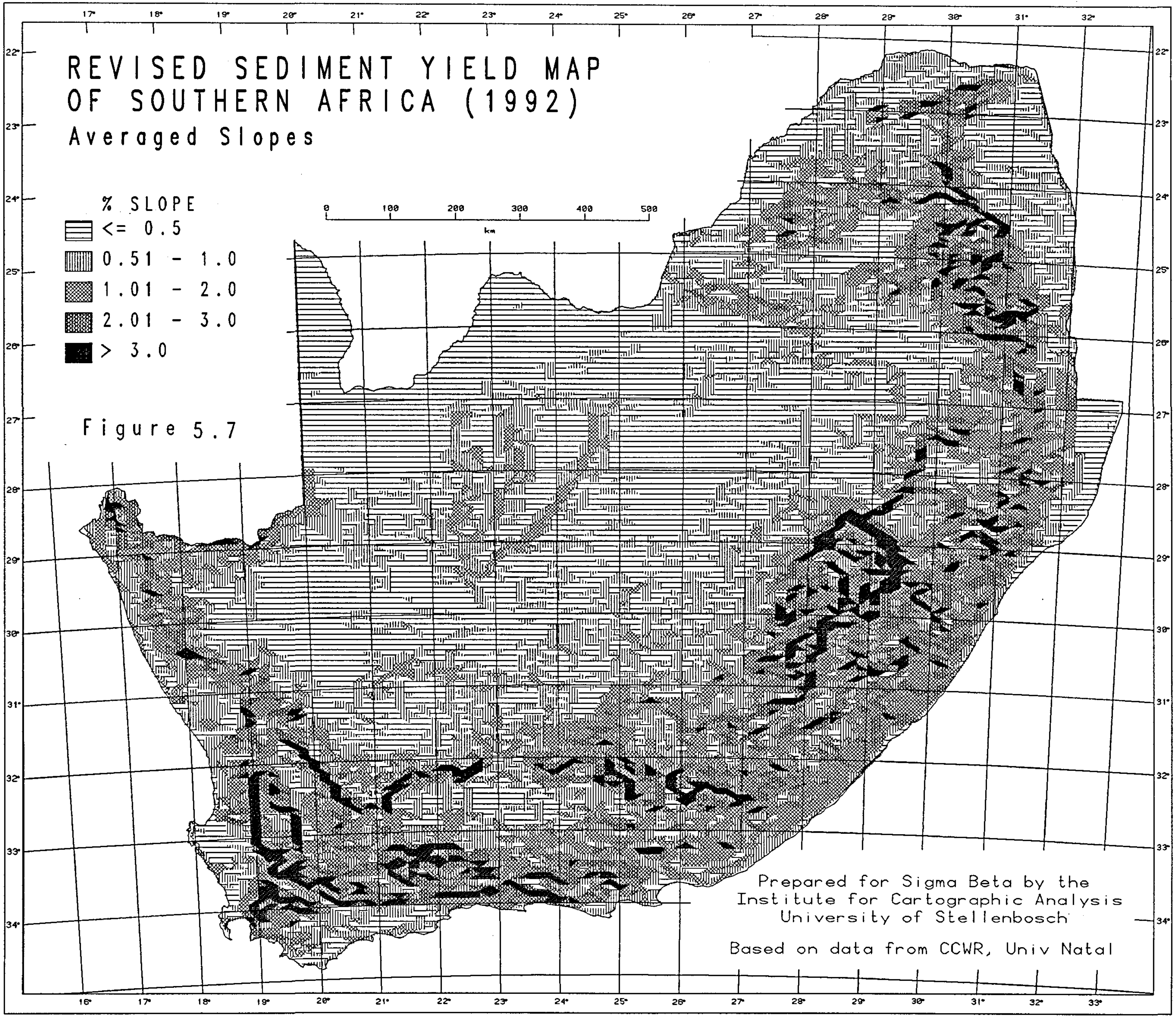
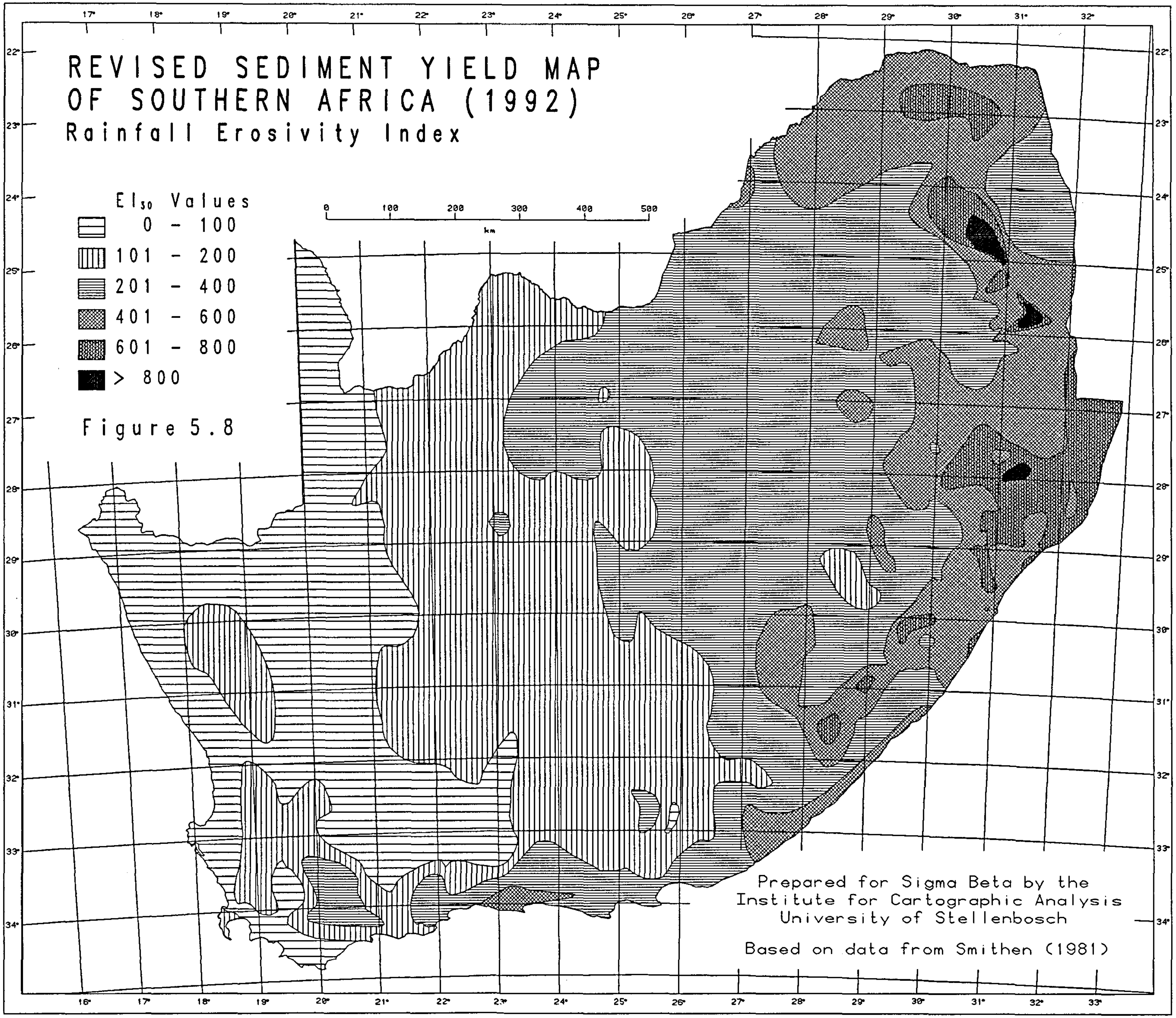

REVISED SEDIMENT YIELD MAP
OF SOUTHERN AFRICA (1992)
Agricultural Regions
Grains
Sugar
Forestry
Vegetables
Fruit
Cattle
Sheep
Diverse
Subsistence
None
0
100
200
300
400
500
km
Prepared for Sigma Beta by the
Institute for Cartographic Analysis
University of Stellenbosch

Figure 5.6


REVISED SEDIMENT YIELD MAP
OF SOUTHERN AFRICA (1992)
Averaged Slopes
% SLOPE
<= 0.5
0.51 - 1.0
1.01 - 2.0
2.01 - 3.0
> 3.0
0 100 200 300 400 500
km
Figure 5.7
Prepared for Sigma Beta by the
Institute for Cartographic Analysis
University of Stellenbosch
Based on data from CCWR, Univ Natal


REVISED SEDIMENT YIELD MAP
OF SOUTHERN AFRICA (1992)
Rainfall Erosivity Index
EI30 Values
0 - 100
101 - 200
201 - 400
401 - 600
601 - 800
> 800
Figure 5.8
0 100 200 300 400 500
km
Prepared for Sigma Beta by the
Institute for Cartographic Analysis
University of Stellenbosch
Based on data from Smithen (1981)

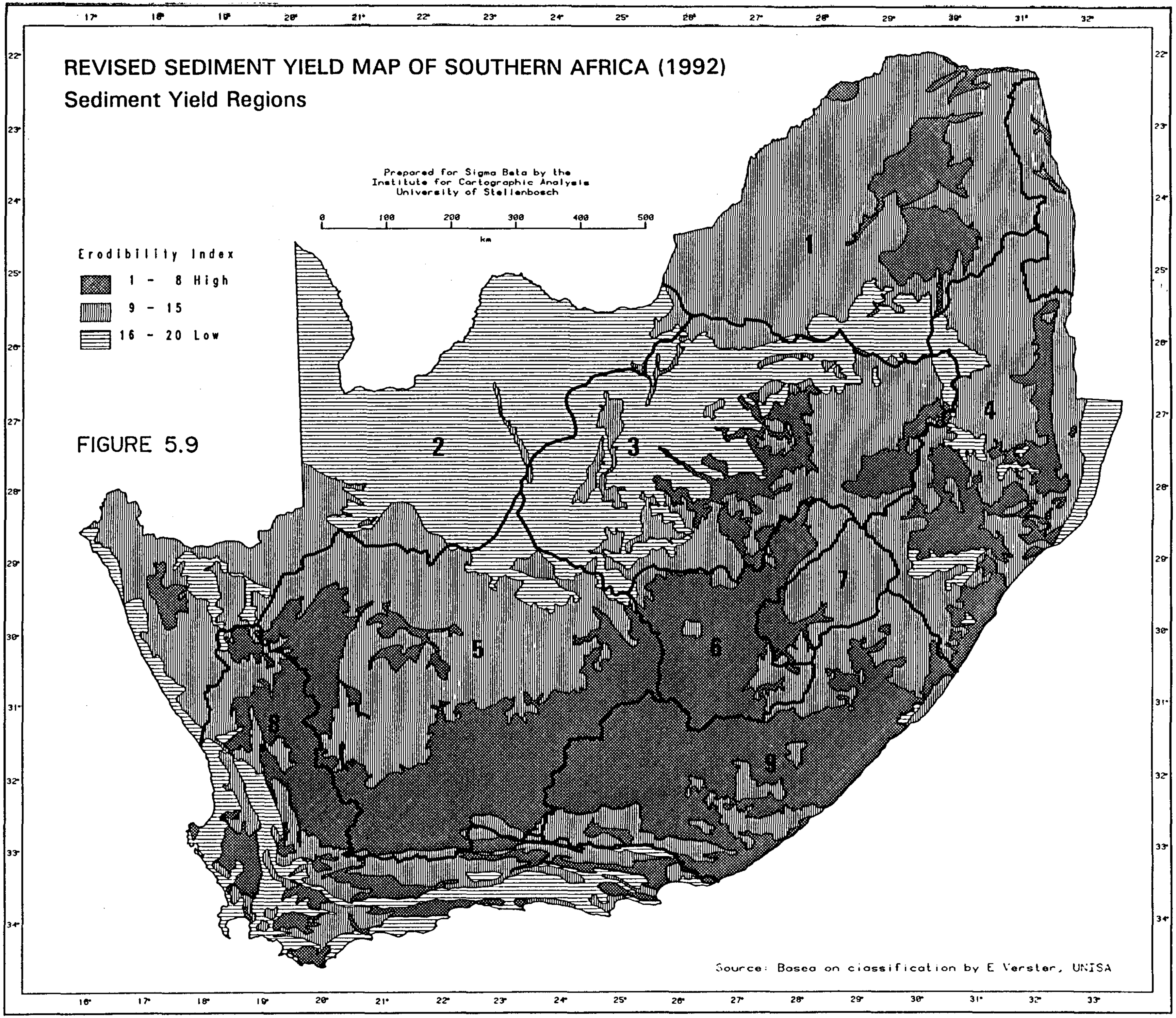

REVISED SEDIMENT YIELD MAP OF SOUTHERN AFRICA (1992)
Sediment Yield Regions
Prepared for Sigma Beta by the
Institute for Cartographic Analysis
University of Stellenbosch
0 100 200 300 400 500
km
Erodibility Index
1 - 8 High
9 - 15
16 - 20 Low
Source: Based on classification by E Verster, UNISA

FIGURE 5.9

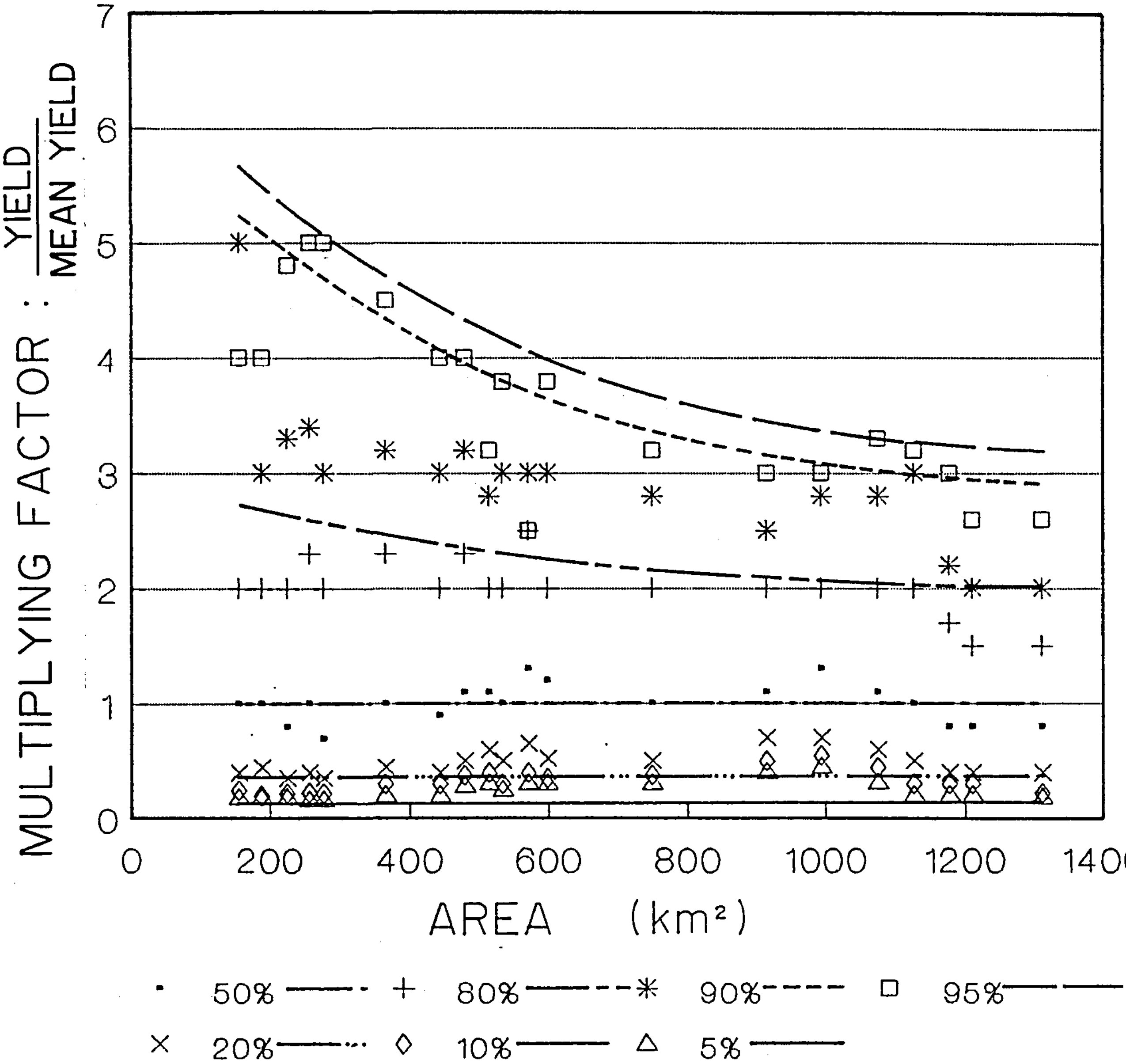



FIG 5.10 REGION I

SEDIMENT YIELD CONFIDENCE BANDS

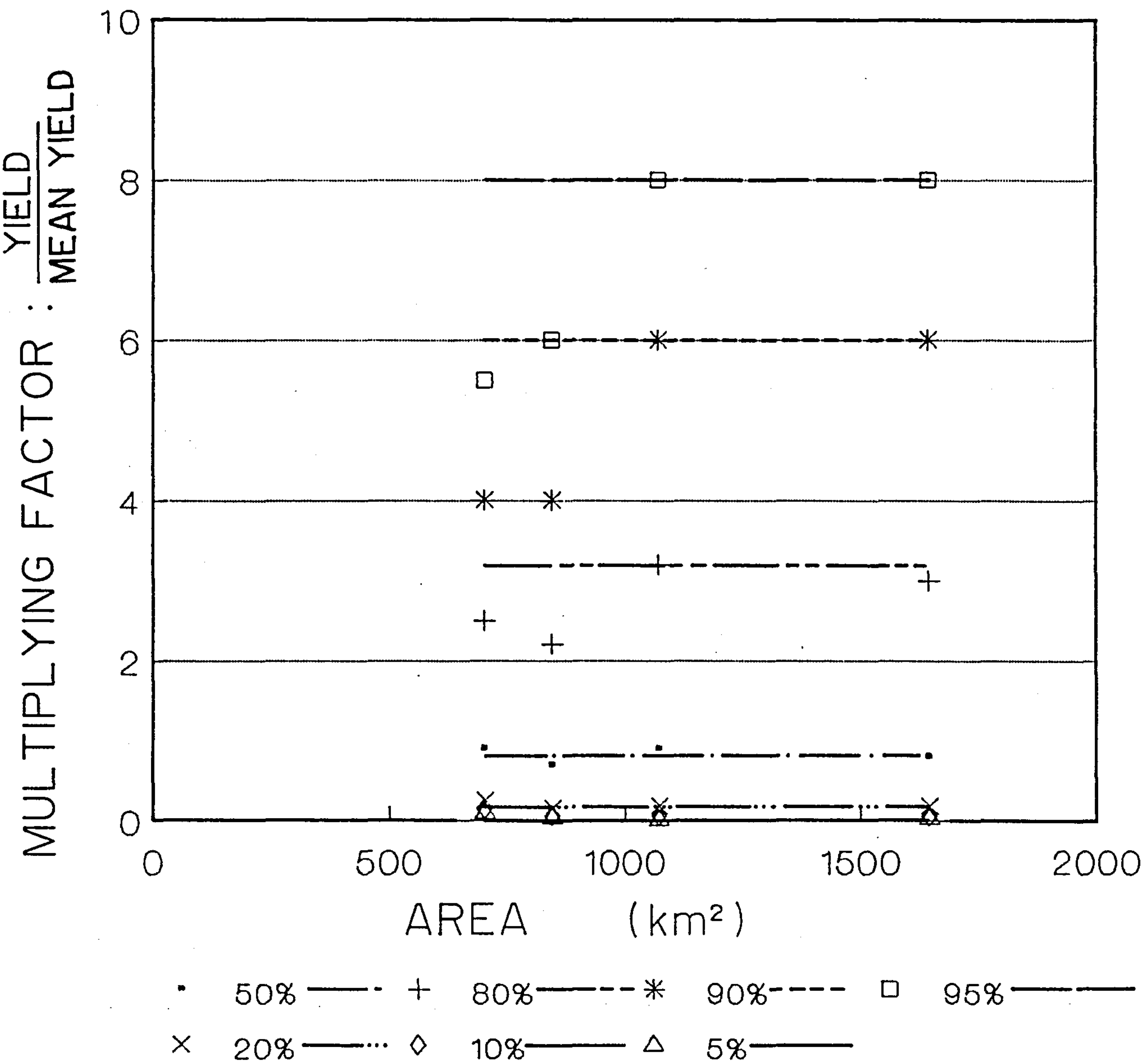



FIG 5.11 REGION 3
SEDIMENT YIELD CONFIDENCE BANDS

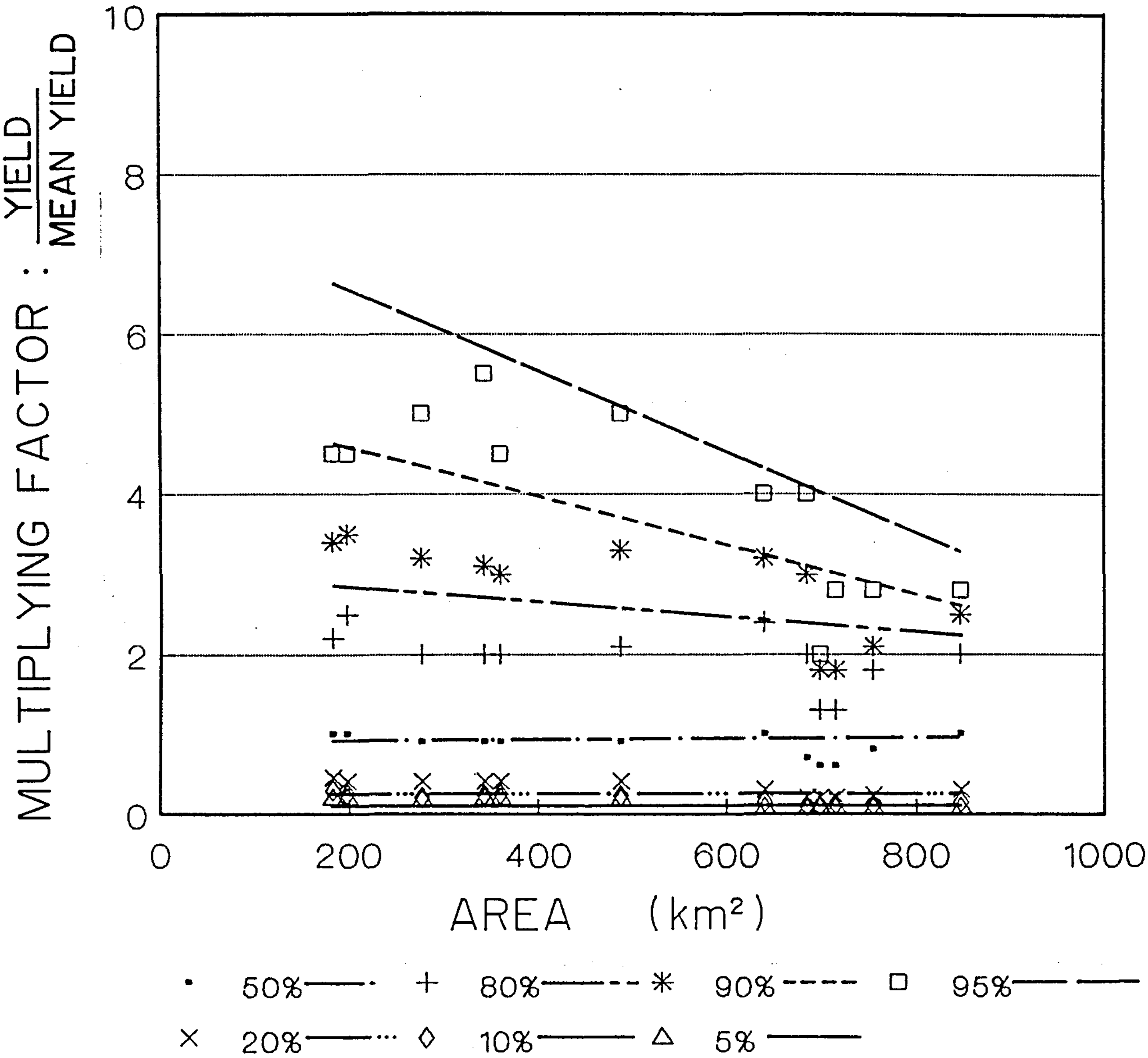



FIG 5.12 REGION 4

SEDIMENT YIELD CONFIDENCE BANDS

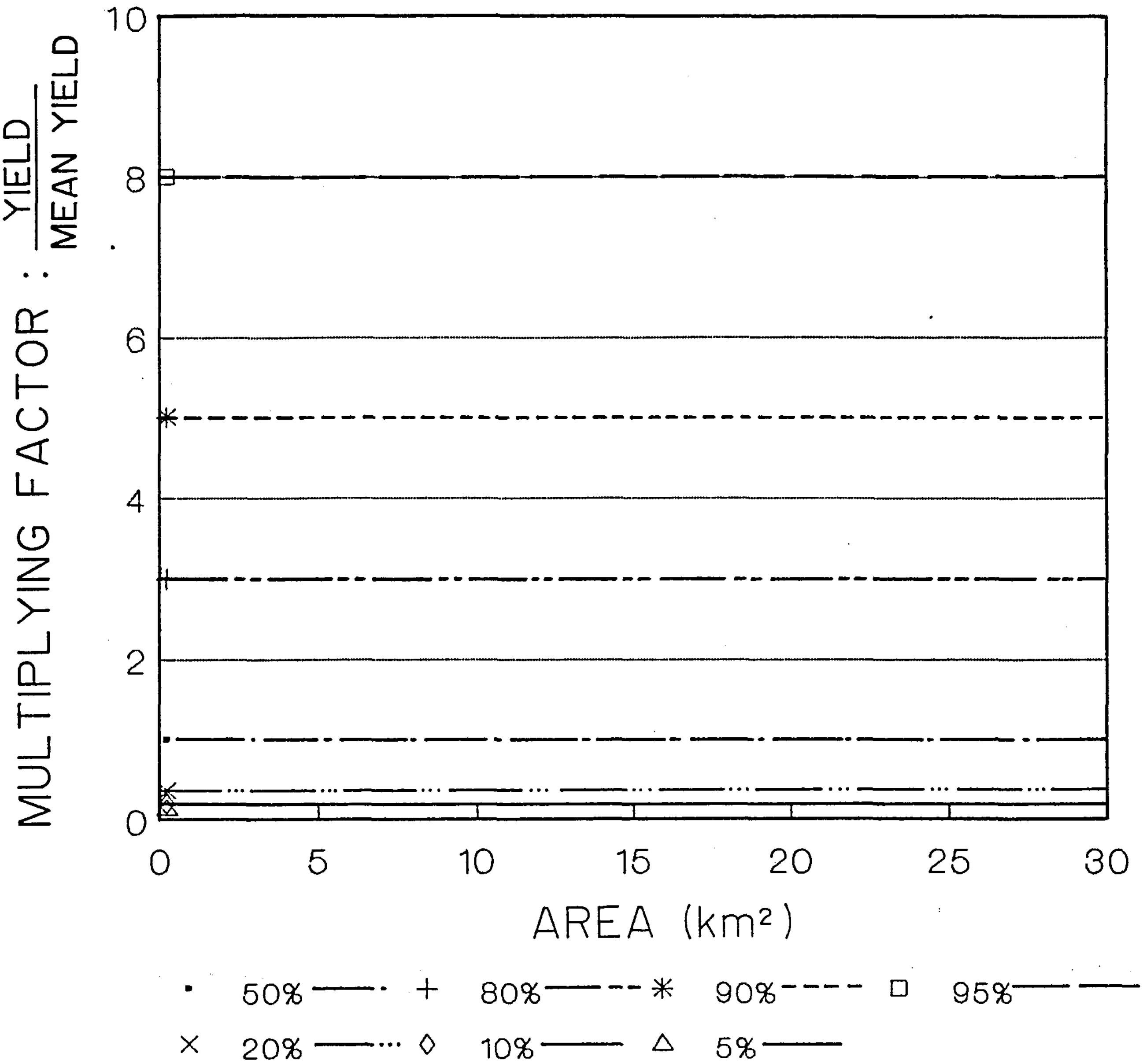



FIG 5.13 REGION 5
SEDIMENT YIELD CONFIDENCE BANDS

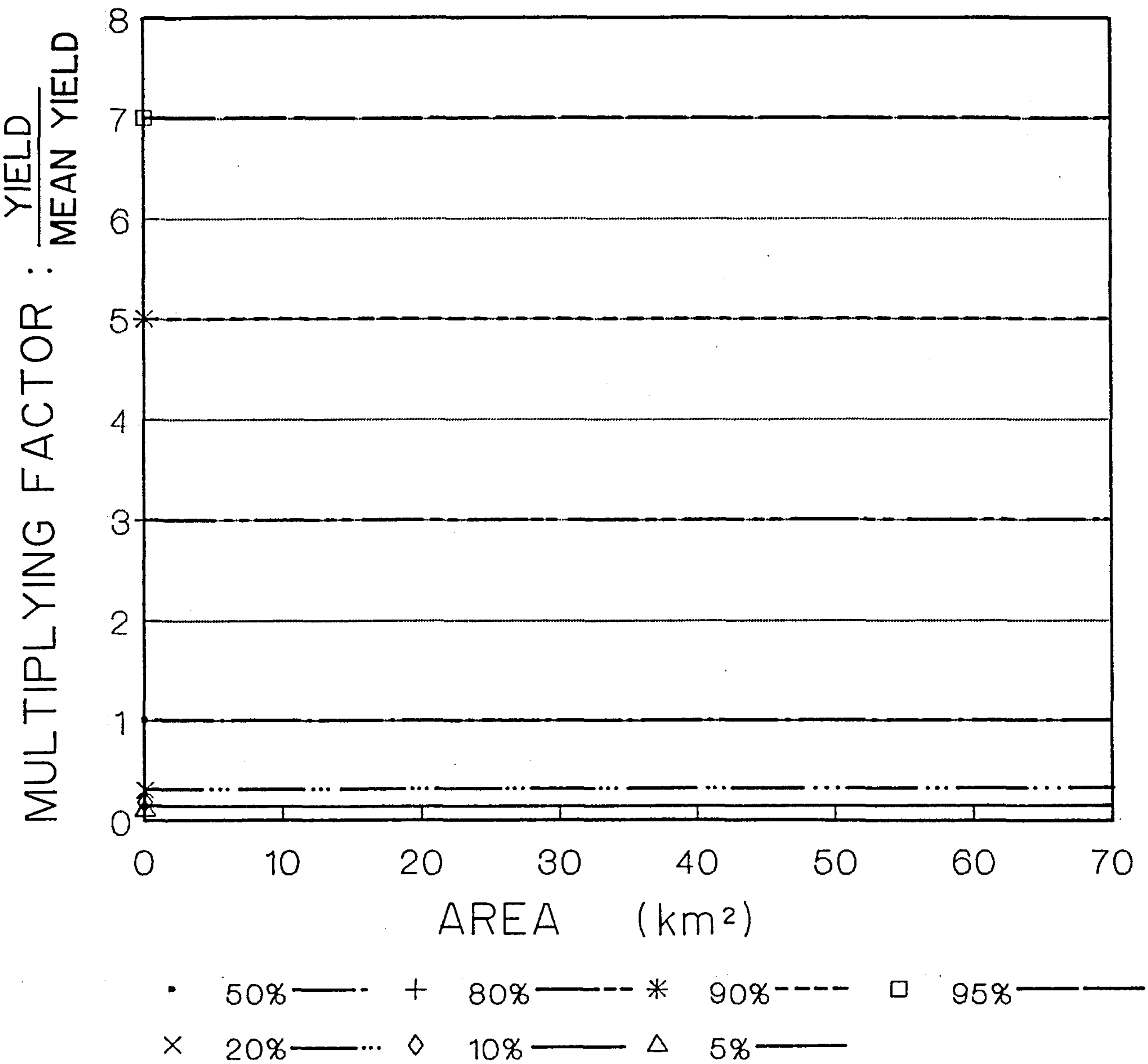



FIG 5.14 REGION 6

SEDIMENT YIELD CONFIDENCE BANDS

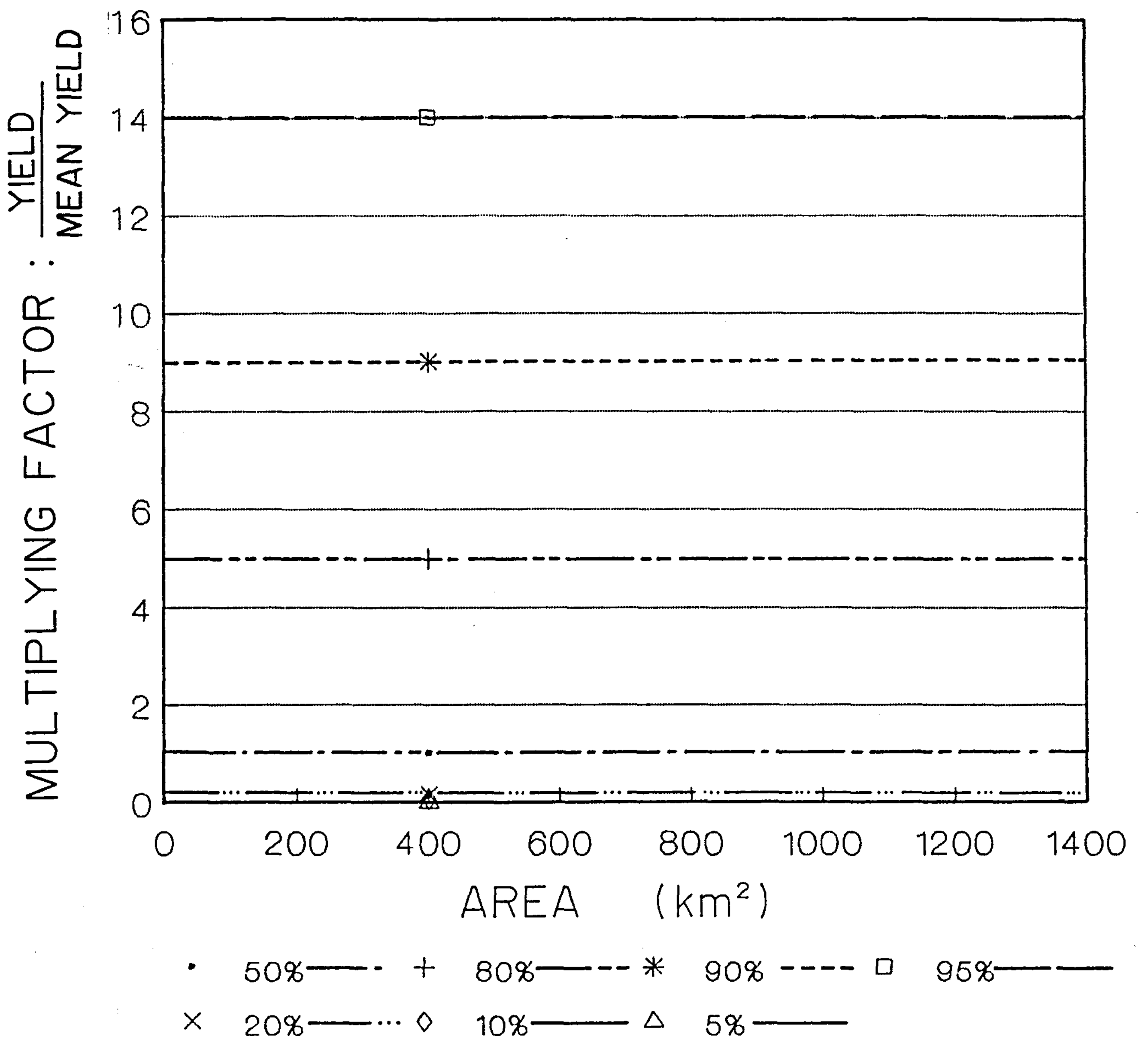



FIG 5.15 REGION 7

SEDIMENT YIELD CONFIDENCE BANDS

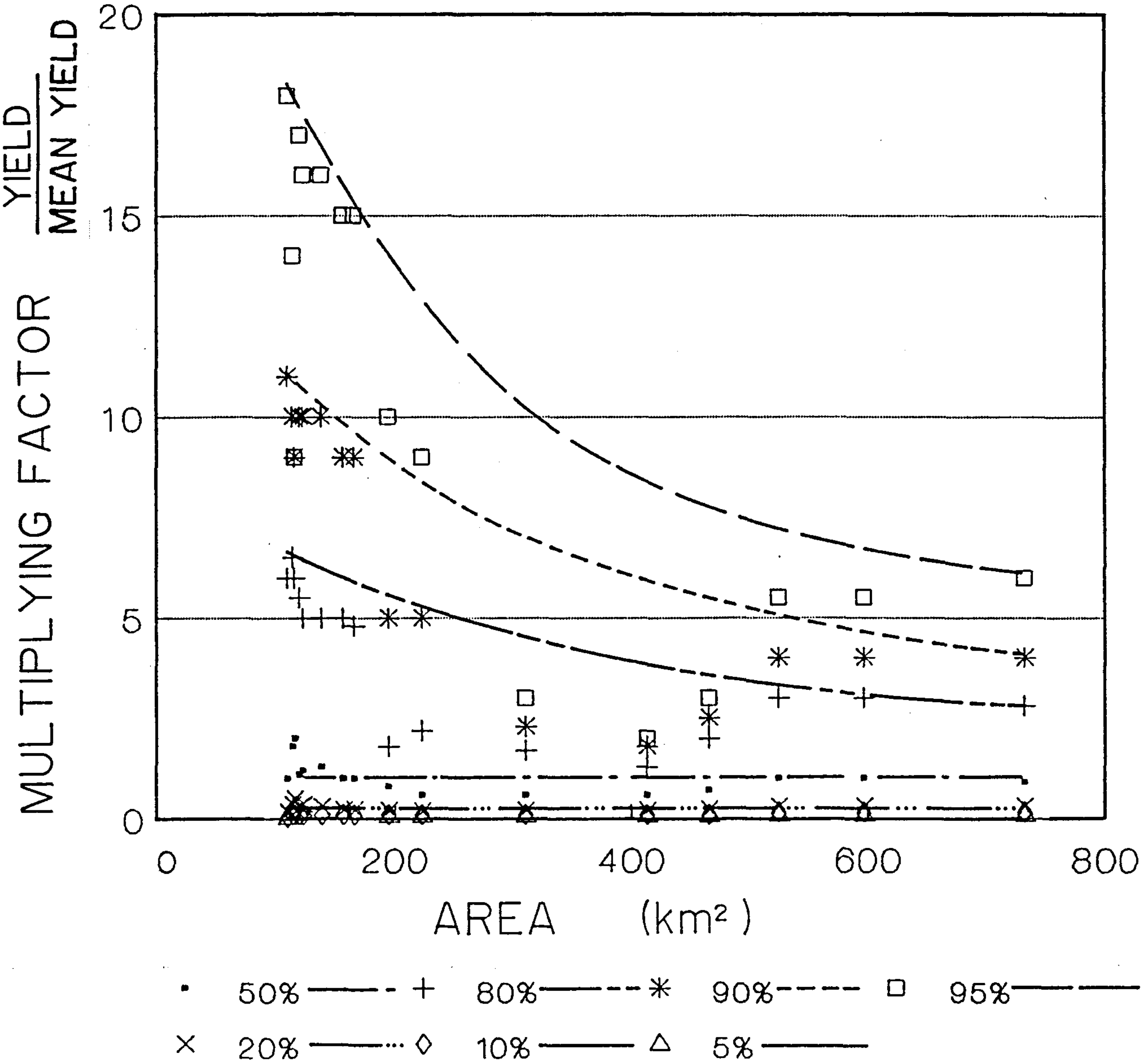



FIG 5.16 REGION 8
SEDIMENT YIELD CONFIDENCE BANDS

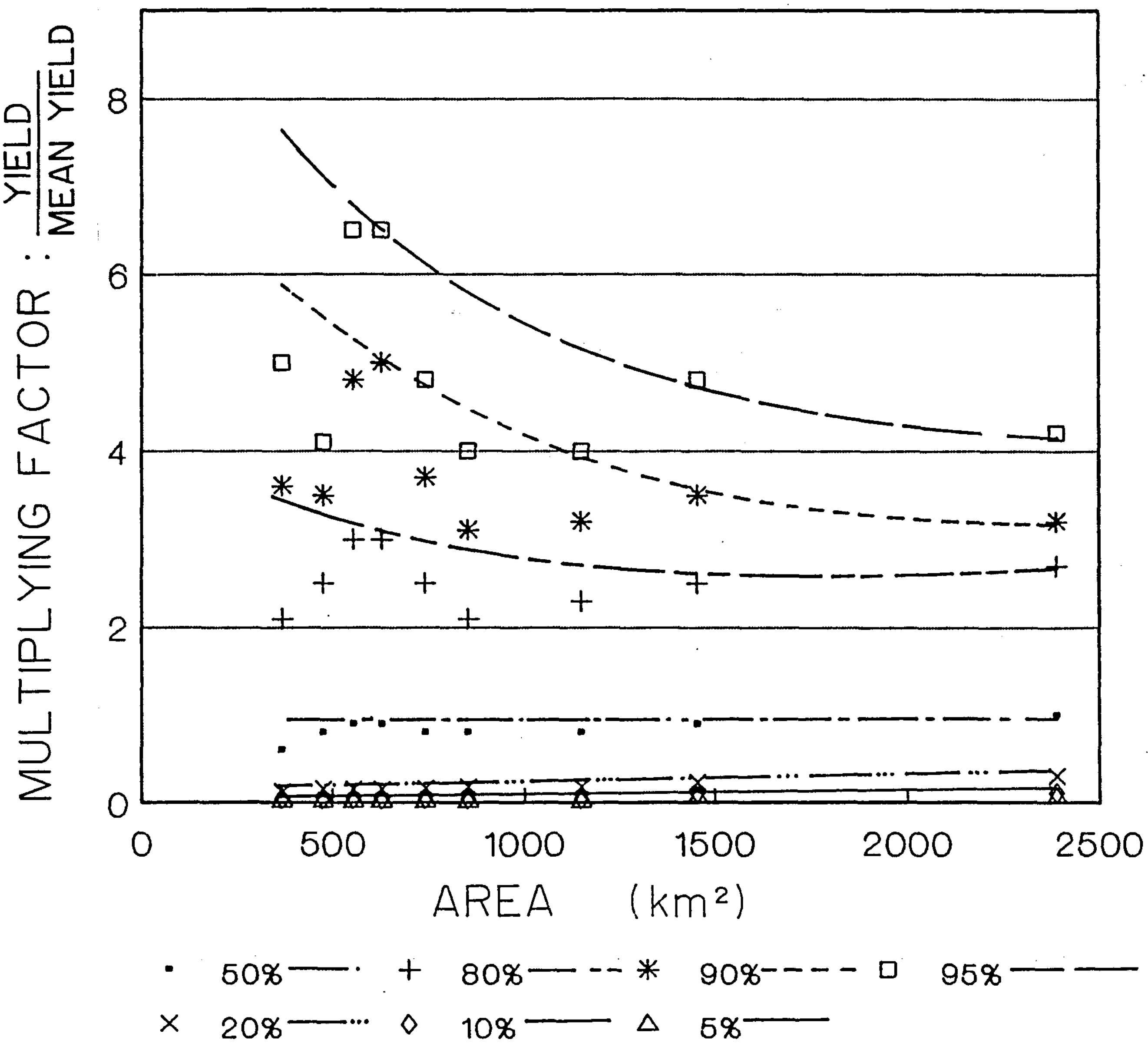



FIG 5.17 REGION 9

SEDIMENT YIELD CONFIDENCE BANDS

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| BRANCH | LOCATION NUMBER | DAM NAME | REGION | PERIOD | $V_W$ (END) ($10^6$ $m^3$) | $V_T$ ($10^6$ $m^3$) | $V_{50}$ ($10^6$ $m^3$) | ECA ($km^2$) | YIELD ($t/km^2.a$) | $V_T/V_W$ (%) | $V_W$ /MAR | $V_W$ /ECA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Blaasbalk | D200-17 | Poortjie | 6 | 1925-1981 | 5.408 | 1.993 | 1.912 | 450 | 115 | 26.9 | - | 12018 |
| Oranje | D350-02 | Hendrik Verwoerd | 6 | 1971-1979 | 5673.778 | 274.989 | 884.691 | 67845 | 352 | 4.6 | 0.66 | 83629 |
| Bethulie | D350-04 | Bethulie | 6 | 1921-1979 | 1.969 | 4.542 | 4.302 | 255 | 455 | 69.8 | 0.34 | 7720 |
| Swartbas | D420-01 | Leeubos | 2 | 1949-1983 | 0.998 | 0.129 | 0.151 | 259 | 16 | 11.4 | 0.72 | 3854 |
| Van Wyksvlei | D540-01 | Van Wyksvlei | 5 | 1884-1979 | 143.081 | 2.248 | 1.300 | 1339 | 26 | 1.5 | - | 106857 |
| Ongers | D600-01 | Smartt | 5 | 1912-1980 | 100.287 | 2.217 | 1.987 | 13114 | 4 | 2.2 | 2.48 | 7647 |
| Dorp | D600-06 | Victoria-Wes | 5 | 1924-1954 | 3.660 | 0.440 | 0.545 | 280 | 53 | 10.7 | - | 13071 |
| Olifants | E100-02 | Clanwilliam | 8 | 1935-1980 | 124.092 | 9.715 | 10.117 | 2033 | 134 | 7.3 | 0.32 | 61039 |
| Olifants | E100-04 | Bulshoek | 8 | 1922-1980 | 6.298 | 0.486 | 0.460 | 736 | 17 | 7.2 | 0.01 | 8557 |
| Wemmershoek | G100-13 | Wemmershoek | 8 | 1957-1984 | 58.797 | 1.102 | 1.434 | 125 | 310 | 1.8 | - | 470373 |
| Stettynskloof | H100-18 | Stettynskloof | 8 | 1954-1984 | 15.543 | 0.088 | 0.109 | 55 | 54 | 0.6 | 0.33 | 282600 |
| Koekedouw | H101-51 | Ceres | 8 | 1953-1981 | 0.347 | 0.018 | 0.023 | 50 | 12 | 4.9 | - | 6968 |
| Sanddrif | H200-07 | Roode Elsburg | 8 | 1968-1983 | 7.744 | 0.373 | 0.682 | 59 | 202 | 4.6 | 0.39 | 131247 |
| Groot | H300-01 | Poortjieskloof | 8 | 1957-1979 | 9.960 | 0.247 | 0.358 | 94 | 103 | 2.4 | 1.38 | 105952 |
| Keisies | H300-02 | Pietersfontein | 8 | 1968-1981 | 2.062 | 0.570 | 1.155 | 116 | 269 | 21.7 | 4.48 | 17774 |
| Nuy | H400-02 | Keerom | 8 | 1954-1981 | 7.398 | 0.946 | 1.232 | 378 | 88 | 11.3 | 1.03 | 19571 |
| Konings | H400-06 | Klipberg | 8 | 1964-1983 | 1.996 | 0.002 | 0.002 | 54 | 1 | 0.1 | 1.80 | 36967 |
| Hoeks | H400-10 | Moordkuil | 8 | 1950-1985 | 1.520 | 0.048 | 0.056 | 176 | 9 | 3.1 | - | 8634 |
| Buffeljags | H700-02 | Buffeljags | 8 | 1966-1983 | 5.736 | 0.090 | 0.152 | 601 | 7 | 1.5 | 0.05 | 9543 |
| Duiwenhoks | H800-03 | Duiwenhoks | 8 | 1965-1979 | 6.406 | 0.058 | 0.112 | 148 | 20 | 0.9 | 0.22 | 43283 |
| Korinte | H900-03 | Korentepoort | 8 | 1965-1983 | 8.296 | 0.028 | 0.045 | 37 | 33 | 0.3 | - | 224224 |
| Buffels | J110-01 | Floriskraal | 6 | 1957-1981 | 51.951 | 15.486 | 25.000 | 4001 | 169 | 23.0 | 2.49 | 12985 |
| Brak | J120-02 | Bellair | 8 | 1920-1981 | 10.077 | 0.933 | 0.700 | 558 | 34 | 8.5 | 0.45 | 18059 |
| Prins | J120-04 | Prinsrivier | 8 | 1916-1981 | 1.262 | 4.189 | 3.813 | 757 | 136 | 76.9 | 0.37 | 1667 |

| BRANCH | LOCATION NUMBER | DAM NAME | REGION | PERIOD | $V_W$ (END) ($10^6$ $m^3$) | $V_T$ ($10^6$ $m^3$) | $V_{50}$ ($10^6$ $m^3$) | ECA ($km^2$) | YIELD ($t/km^2.a$) | $V_T/V_W$ (%) | $V_W$ /MAR | $V_W$ /ECA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Gamka | J210-01 | Gamka | 5 | 1955-1980 | 2.165 | 0.187 | 0.253 | 98 | 70 | 7.9 | 0.50 | 22092 |
| Leeu | J220-01 | Leeu Gamka | 5 | 1959-1981 | 14.154 | 7.478 | 10.818 | 2088 | 140 | 34.6 | 0.49 | 6779 |
| Cordiers | J230-01 | Oukloof | 5 | 1929-1984 | 4.222 | 0.293 | 0.283 | 141 | 54 | 6.5 | 1.13 | 29945 |
| Gamka | J250-01 | Gamkapoort | 5 | 1969-1981 | 43.836 | 10.122 | 21.849 | 17076 | 35 | 18.8 | 1.09 | 2567 |
| Nels | J250-02 | Calitzdorp | 8 | 1917-1981 | 4.817 | 0.997 | 0.850 | 170 | 135 | 17.2 | 0.67 | 28334 |
| Olifants | J330-01 | Stompdrift | 8 | 1965-1981 | 55.316 | 6.438 | 11.265 | 5235 | 58 | 10.4 | 2.27 | 10567 |
| Kammanassie | J340-02 | Kammanassie | 8 | 1923-1981 | 35.855 | 3.584 | 3.000 | 1505 | 54 | 9.1 | 0.98 | 23824 |
| L/Le Roux | J350-04 | Raubenheimer | 8 | 1973-1984 | 9.203 | 0.005 | 0.011 | 43 | 7 | 0.1 | 0.52 | 150875 |
| L/Le Roux | J350-05 | Melville | 8 | 1945-1984 | 0.466 | 0.001 | 0.001 | 18 | 1 | 0.2 | - | 25900 |
| Hartenbos | K100-02 | Hartebeeskuil | 8 | 1969-1981 | 7.162 | 0.011 | 0.024 | 100 | 7 | 0.2 | 4.07 | 71615 |
| G/Brak | K100-06 | Ernest Robertson | 8 | 1955-1985 | 0.419 | 0.004 | 0.004 | 10 | 12 | 0.9 | 0.11 | 41940 |
| Krom | K900-01 | Churchill | 8 | 1943-1987 | 35.678 | 0.122 | 0.128 | 357 | 10 | 0.3 | - | 99939 |
| Koega | L820-1 | Paul Sauer | 8 | 1969-1986 | 128.490 | 1.515 | 2.549 | 3887 | 18 | 1.2 | 0.64 | 33056 |
| Loerie | L900-01 | Loerie | 8 | 1971-1984 | 3.362 | 0.752 | 1.524 | 147 | 280 | 18.3 | 0.08 | 22869 |
| Sondags | N120-01 | Van Ryneveldspas | 9 | 1925-1978 | 47.426 | 31.397 | 27.500 | 3544 | 210 | 39.8 | 1.40 | 13382 |
| Sondags | M230-01 | Lake Mentz | 9 | 1922-1978 | 191.758 | 135.670 | 130.140 | 12987 | 271 | 41.4 | 1.09 | 14765 |
| Nuwejaars | P100-01 | Nuwejaars | 9 | 1958-1981 | 4.622 | 0.057 | 0.081 | 531 | 4 | 1.2 | - | 8704 |
| G/Brak | Q130-01 | Grassridge | 9 | 1924-1984 | 49.576 | 41.252 | 38.610 | 4325 | 241 | 45.4 | 0.55 | 11463 |
| Tarka | Q410-01 | Kommandodrif | 9 | 1956-1985 | 58.800 | 14.663 | 21.000 | 3623 | 157 | 20.0 | 1.68 | 16230 |
| Tarka | Q440-01 | Lake Arthur | 9 | 1924-1985 | 29.255 | 68.059 | 63.331 | 3450 | 496 | 69.9 | 0.46 | 8480 |
| G/Vis | Q500-01 | Elandsdrift | 9 | 1973-1981 | 9.720 | 2.459 | 7.912 | 8042 | 27 | 20.2 | - | 1209 |
| Kat | Q940-01 | Katrivier | 9 | 1969-1988 | 24.873 | 1.887 | 2.966 | 258 | 310 | 7.6 | 1.18 | 96319 |
| Buffels | R200-02 | Laing | 9 | 1950-1981 | 21.035 | 1.708 | 2.400 | 862 | 75 | 7.5 | 0.34 | 24403 |
| Buffels | R200-05 | Bridle Drift | 9 | 1968-1981 | 73.509 | 5.146 | 10.430 | 375 | 751 | 6.5 | 0.71 | 196023 |

| BRANCH | LOCATION NUMBER | DAM NAME | REGION | PERIOD | $V_W$ (END) ($10^6$ $m^3$) | $V_T$ ($10^6$ $m^3$) | $V_{50}$ ($10^6$ $m^3$) | ECA ($km^2$) | YIELD ($t/km^2.a$) | $V_T/V_W$ (%) | $V_W$ /MAR | $V_W$ /ECA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Buffels | R200-07 | Maden | 9 | 1909-1981 | 0.266 | 0.053 | 0.047 | 30 | 42 | 16.8 | - | 8850 |
| Nahoon | R300-01 | Nahoon | 9 | 1964-1981 | 20.759 | 1.201 | 2.021 | 474 | 115 | 5.5 | 0.52 | 43795 |
| Wit Kei | S100-01 | Xonxa | 9 | 1974-1986 | 135.080 | 22.486 | 48.536 | 1487 | 881 | 14.3 | - | 90841 |
| Doring | S200-01 | Indwe | 9 | 1969-1984 | 23.444 | 3.864 | 7.061 | 295 | 646 | 14.1 | - | 79471 |
| Klipplaat | S300-06 | Waterdown | 9 | 1958-1988 | 38.200 | 0.213 | 0.264 | 603 | 12 | 0.6 | 0.72 | 63350 |
| Tsomo | S500-01 | Ncora | 9 | 1976-1988 | 154.076 | 8.193 | 17.686 | 1772 | 269 | 5.0 | - | 86951 |
| Gubu | S600-04 | Gubu | 9 | 1970-1981 | 9.254 | 0.059 | 0.137 | 23 | 161 | 0.6 | 2.16 | 402330 |
| Mtata | T201-03 | Mtata | 9 | 1977-1987 | 257.097 | 1.129 | 2.859 | 868 | 89 | 0.4 | - | 296195 |
| Umgeni | U200-01 | Albert Falls | 4 | 1974-1983 | 289.167 | 0.295 | 0.832 | 716 | 31 | 0.1 | 1.14 | 403864 |
| Umgeni | U200-03 | Midmar | 4 | 1965-1983 | 177.114 | 0.204 | 0.330 | 928 | 10 | 0.1 | 1.01 | 190855 |
| Umzinduzi | U200-09 | Henley | 4 | 1942-1987 | 5.407 | 0.355 | 0.370 | 238 | 42 | 6.2 | - | 22717 |
| Mdloti | U300-01 | Hazelmere | 4 | 1975-1987 | 19.223 | 4.679 | 10.099 | 377 | 723 | 19.6 | 0.33 | 50989 |
| Mlazi | U600-03 | Shongweni | 4 | 1927-1987 | 5.208 | 6.853 | 6.414 | 750 | 231 | 56.8 | - | 6945 |
| Tugela | V100-01 | Spioenkop | 4 | 1972-1986 | 279.628 | 6.367 | 12.214 | 774 | 426 | 2.2 | 0.50 | 361276 |
| Mnyamvubu | V200-02 | Craigie Burn | 4 | 1963-1983 | 23.446 | 0.108 | 0.164 | 152 | 29 | 0.5 | 0.88 | 154253 |
| Ngagane | V300-04 | Chelmsford | 4 | 1961-1983 | 198.438 | 3.400 | 4.919 | 830 | 160 | 1.7 | 1.17 | 239081 |
| Boesmans | V700-01 | Wagendrift | 4 | 1963-1983 | 58.362 | 1.639 | 2.500 | 744 | 91 | 2.7 | 0.28 | 78444 |
| Hluhluwe | W300-03 | Hluhluwe | 4 | 1964-1985 | 28.775 | 2.517 | 3.736 | 734 | 137 | 8.0 | 0.72 | 39202 |
| Pongola | W440-01 | Pongolapoort | 4 | 1973-1984 | 2445.258 | 55.656 | 129.262 | 7831 | 446 | 2.2 | 4.54 | 312254 |
| Mpapa | W530-03 | Jericho | 4 | 1966-1983 | 59.834 | 1.011 | 1.701 | 218 | 211 | 1.7 | 1.32 | 274470 |
| Usutu | W540-01 | Westoe | 4 | 1968-1980 | 61.011 | 0.044 | 0.096 | 531 | 5 | 0.1 | 1.35 | 114898 |
| Komati | X100-09 | Nooitgedacht | 4 | 1962-1983 | 78.824 | 1.162 | 1.724 | 1569 | 30 | 1.5 | 1.39 | 50238 |
| Wit | X200-04 | Primkop | 4 | 1970-1987 | 2.017 | 0.191 | 0.322 | 158 | 55 | 8.7 | 0.08 | 12763 |
| Wit | X200-13 | Longmere | 4 | 1940-1979 | 4.347 | 0.227 | 0.250 | 27 | 250 | 5.0 | 0.26 | 161000 |

| BRANCH | LOCATION NUMBER | DAM NAME | REGION | PERIOD | $V_W$ (END) ($10^6$ $m^3$) | $V_T$ ($10^6$ $m^3$) | $V_{50}$ ($10^6$ $m^3$) | ECA ($km^2$) | YIELD ($t/km^2.a$) | $V_T/V_W$ (%) | $V_W$ /MAR | $V_W$ /ECA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sand | X200-20 | Witteklip | 4 | 1969-1979 | 12.972 | 0.150 | 0.379 | 64 | 160 | 1.1 | 0.78 | 202691 |
| Wit | X200-23 | Klipkopjes | 4 | 1960-1979 | 11.866 | 0.430 | 0.676 | 78 | 234 | 3.5 | - | 152131 |
| Witwaters | X300-02 | Da Gama | 4 | 1971-1979 | 13.653 | 0.404 | 1.300 | 62 | 566 | 2.9 | 1.10 | 220202 |
| Klip | - | Windsor | 4 | - | - | - | 1.087 | 2329 | 126 | - | - | - |
| Mgeni | - | Camperdown | 4 | 1901-1923 | 1.364 | 0.909 | 1.170 | 376 | 84 | 0.67 | - | 3628 |

REGION = SEDIMENT YIELD REGION (SECT 3.7)

$V_W$(END) = VOLUME OF RESERVOIR AT MOST RECENT SURVEY

$V_T$ = VOLUME OF SEDIMENT DEPOSIT

$V_{50}$ = EQUIVALENT 50 YEAR SEDIMENT DEPOSIT VALUE

ECA = EFFECTIVE CATCHMENT AREA

YIELD = ANNUAL YIELD PER UNIT AREA (MASS)

MAR = MEAN ANNUAL RUN-OFF

| STATION | RIVER | ID | REG | TOTAL AREA | PERIOD 1929 - 1934 | 1934 - 1943 | 1943 - 1952 | 1952 - 1960 | 1960 - 1969 |
|---|---|---|---|---|---|---|---|---|---|
| Oranjedraai | Orange | 6 | 6 | 24876 | - | - | - | - | 402 |
| Aliwal-North | Orange | 5 | 6 | 37202 | 414 | 366 | 470 | 530 | 462 |
| Jammersdrift | Caled. | 9 | 6 | 13320 | 923 | 871 | - | - | - |
| Bethulie | Orange | 23 | 6 | 65151 | 646 | 536 | 657 | 669 | 560 |
| Oranjerivierbrug | Orange | 17 | 5 | 94464 | 630 | 493 | 562 | - | - |
| Barrage | Vaal | 22 | 3 | 45882 | 85 | - | - | - | - |
| Paardeberg | Modder | 15 | 3 | 14791 | - | - | 311 | - | - |
| Leeuwkraal | Riet | 16 | 3 | 11000 | 100 | - | - | - | - |
| Prieska/ Upington | | 18/20 | 3 | 329582 | 311 | 196 | 183 | 161 | 119 |

**TABLE 5.2.2(a): AVERAGE SEDIMENT TRANSPORT YIELDS AT VARIOUS MEASURING STATIONS (ORANGE RIVER SYSTEM) ($t/km^2.a$) [ROOSEBOOM AND MAAS - 1974]**

| STATION | RIVER | ID | REG* | AREA $km^2$ | YIELD $t/km^2.a$ | PERIOD |
|---|---|---|---|---|---|---|
| Colenso | Tugela | 19 | 4 | 4203 | 571 | 1950 - 1958 |
| Intulembi | Pongola | 14 | 4 | 7147 | 133 | 1928 - 1945 |
| Burghersdorp | Stormberg | - | 6 | 2370 | 762 | 1935 - 1948 |
| Standerton | Vaal | - | 3 | 8254 | 193 | 1929 - 1940 |
| Vetrivierbrug | Vet | 21 | 3 | 5504 | 279 | 1935 - 1947 |
| Schweizer Reneke | Hartz | - | 3 | 9251 | 7 | 1934 - 1956 |
| Sannaspos | Modder | 28 | 3 | 1650 | 304 | 1935 - 1943 |
| Jansenville | Sondags | 27 | 9 | 11560 | 136 | 1930 - 1948 |
| Buffelsfontein | L/Fish | 26 | 9 | 995 | 589 | 1931 - 1939 |
| Hougham Abramson | G/Fish | 30 | 9 | 18436 | 209 | 1930 - 1940 |
| Upsher | Kat | 25 | 9 | 554 | 499 | 1931 - 1948 |

*REG = SEDIMENT YIELD REGION (SECTION 3.7)

**TABLE 5.2.2(b): OTHER YIELD DATA DERIVED FROM STREAM SAMPLING**

| LOC. No. | STATION | RIVER | ID | REG* | AREA ($km^2$) | YIELD ($t/km^2.a$) | PERIOD |
|---|---|---|---|---|---|---|---|
| SG3 | Seaka | Senqu | 8 | 6 | 8975 | 295 | 1976-1982 |
| SG4 | Whitehill | Senqu | 1 | 7 | 2950 | 329 | 1976-1982 |
| SG45 | Ha Lejone | Malibamatso | 4 | 7 | 1157 | 9 | 1976-1982 |
| SG5 | Koma-Koma | Senqu | 2 | 7 | 2198 | 89 | 1976-1982 |
| SG8 | Paray | Malibamatso | 3 | 7 | 1018 | 175 | 1976-1982 |
| CG24 | Masianokeng | S. Phutiatsana | 10 | 6 | 945 | 1382 | 1976-1982 |
| CG34 | Mapoteng | N. Phutiatsana | 11 | 7 | 386 | 2050 | 1976-1982 |
| CG38 | Mashili | Caledon | 12 | 6 | 1348 | 832 | 1976-1982 |
| CG39 | Mohlokagala | Caledon | 13 | 6 | 3312 | 1055 | 1976-1982 |

*REG = SEDIMENT YIELD REGION (SECTION 3.7)

**TABLE 5.2.2(c): LESOTHO SEDIMENT YIELD VALUES (MAKHOALIBE - 1984)**

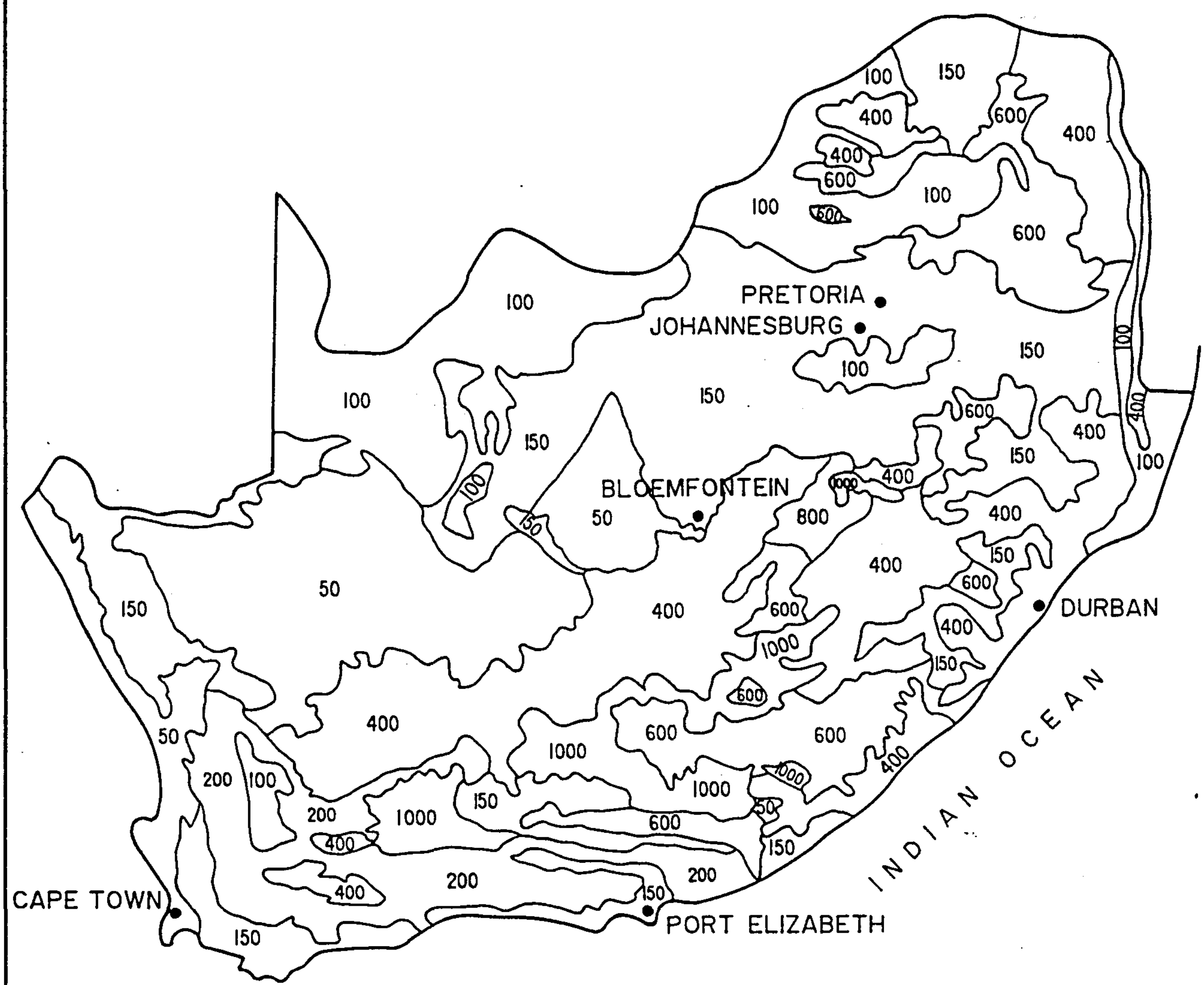


FIGURE 5.1 : THE 1978 SEDIMENT YIELD MAP FOR SOUTHERN AFRICA : INDICATING MAXIMUM OBSERVED YIELD VALUES