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The new sediment yield map for southern Africa

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ABSTRACT Serious erosion, reservoir sedimentation and other sediment-related phenomena pose serious problems in Africa. Regular monitoring of sediment loads in rivers was started in South Africa in 1929 with the result that South Africa possesses some of the most comprehensive records of sediment loads in rivers currently available. These records have been used to prepare sediment yield maps for the southern African region on different occasions since 1952. A completely new map has been prepared for publication during 1992. This paper deals with the methodologies which have been used in preparing the map as well as the lessons which have been learnt in the process.

INTRODUCTION

The significance of sediment-related problems in southern Africa is evident from the more than 600 references which are included in the "Bibliography on Soil Erosion and Sediment Production Research in Southern Africa" (Weaver, 1989). Africa is a very old continent with limited soil cover and therefore high erosion rates cannot be afforded. High erosion rates tend to lead to rapid deterioration of agricultural potential as well as sedimentation of storage reservoirs. Reservoir sedimentation was first identified as a serious problem in 1901 when the newly constructed Camperdown dam's basin suffered rapid build-up of sediment. Ad hoc river sediment sampling was initiated in 1919 and a regular sampling programme (daily sampling) was commenced in 1929. Through the years the emphasis in monitoring of sediment loads has shifted from stream sampling to regular resurveying of existing reservoir basins in order to record sediment accumulation. Recorded yields have been extrapolated to develop generalized sediment yield maps for the region, mainly for predicting sedimentation rates of planned reservoirs in ungauged catchments. These maps (Midgley, 1952; Schwartz & Pullen, 1966; Rooseboom, 1978) tended to provide conservatively high yield values for planning and design purposes. The most recent map (1978) was based on data which had been available up to 1974 and it became necessary to develop a new map. This was undertaken under the sponsorship of the South African Water Research Commission (Rooseboom et al., 1992).

From wide-ranging enquiries it was clear that the previous map has been used and mis-used extensively. Whilst the map was intended mainly 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 do 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, it is difficult to quantify and to relate such changes to specific parameters. It takes at least six years of continuous monitoring to obtain a reasonable estimate of the average sediment load of a typical local river. Much longer records are therefore required to identify persistent changes in yields. One of the few cases where a long continuous comparable record exists (1929 - 1969) was reported on by Rooseboom & Harmse (1979). 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 sediment 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.

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 121 reservoirs were used to determine yields for the appropriate catchments. 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 (Fig. 1) 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. 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.

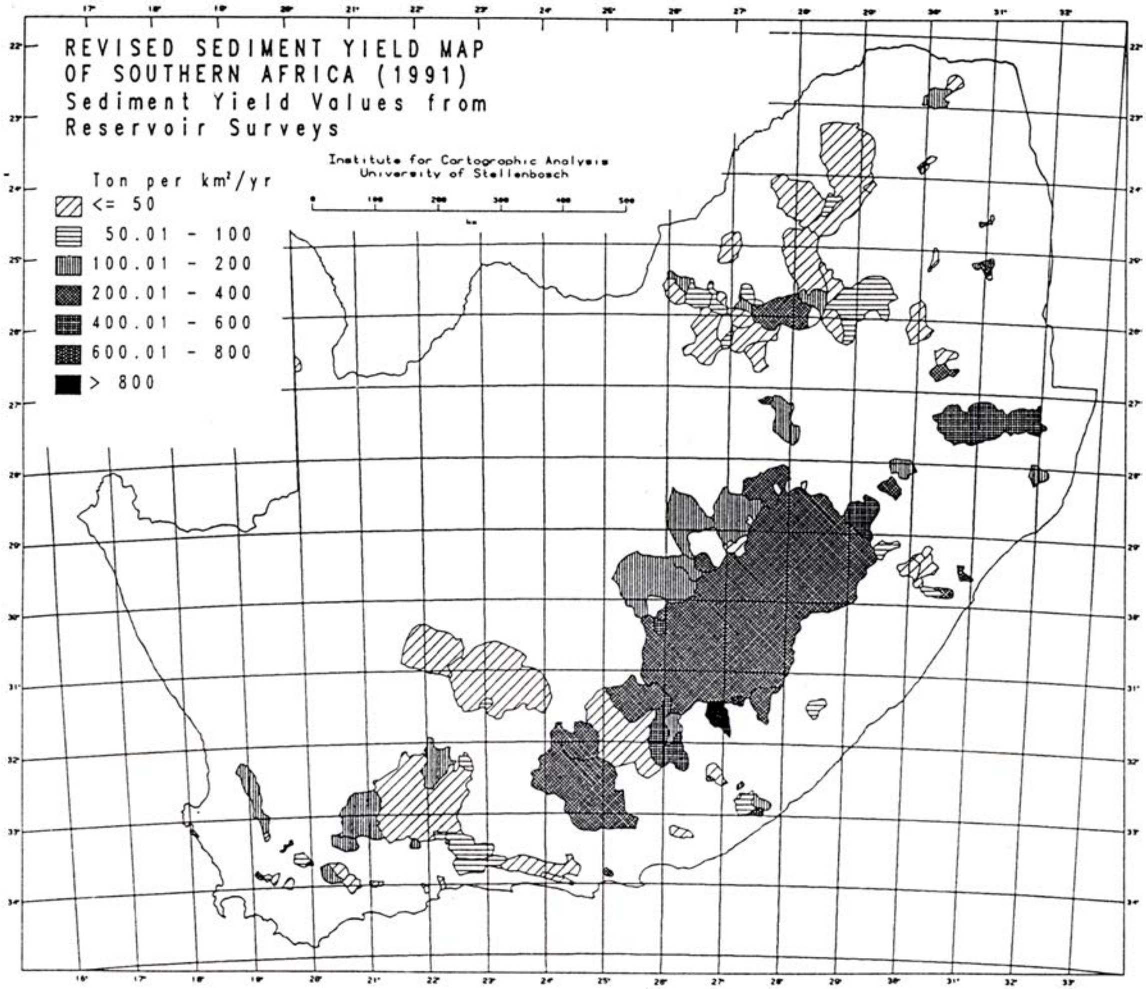
REVISED SEDIMENT YIELD MAP
OF SOUTHERN AFRICA (1991)
Sediment Yield Values from
Reservoir Surveys
Institute for Cartographic Analysis
University of Stellenbosch
Ton per km²/yr
<= 50
50.01 - 100
100.01 - 200
200.01 - 400
400.01 - 600
600.01 - 800
> 800

FIG. 1

Various base maps were prepared for the study. These included a basic erodibility map based mainly on soii types which was eventually simplified to Fig. 2, agricultural land-use regions (Fig. 3) and an average slope map (Fig. 4) as well as rainfall intensity maps.

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; α_1, α_2, α_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 α 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 too much variation in unit sediment yields for regions which were deemed to deliver constant yields and that certain simplyfying assumptions would have to be made in order to come to a workable solution. It was also necessary to determine whether unit yields could be linked to the sediment-carrying capacity of catchment runoff. A deterministic model was developed for this purpose.

DETERMINISTIC MODEL

One of the approaches used in the analysis was to develop a mathematical model (Rooseboom et al., 1992) which would describe the transporting capacity of runoff 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 & Mülke, 1982) on the one hand and in modelling sediment movement through reservoirs on the other extreme (Rooseboom & Van Vuuren, 1988) this approach was used for depicting the sediment carrying capacity of runoff

The model was based on:
(a) the rational formula to determine run-off discharge.
(b) the continuity and Chezy equations to convert discharge into flow velocities and depths.

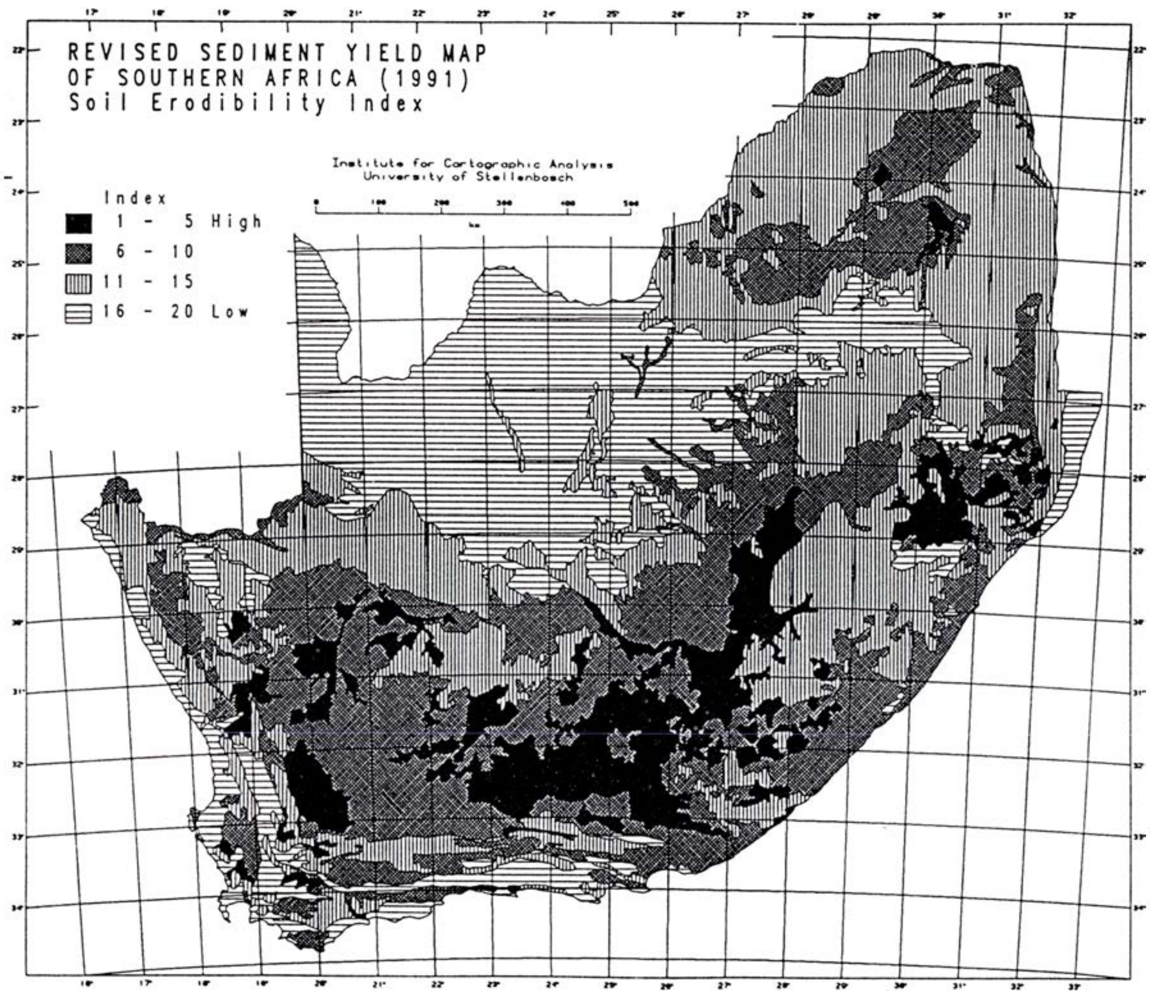
REVISED SEDIMENT YIELD MAP
OF SOUTHERN AFRICA (1991)
Soil Erodibility Index
Institute for Cartographic Analysis
University of Stellenbosch
Index
1 - 5 High
6 - 10
11 - 15
16 - 20 Low

FIG. 2

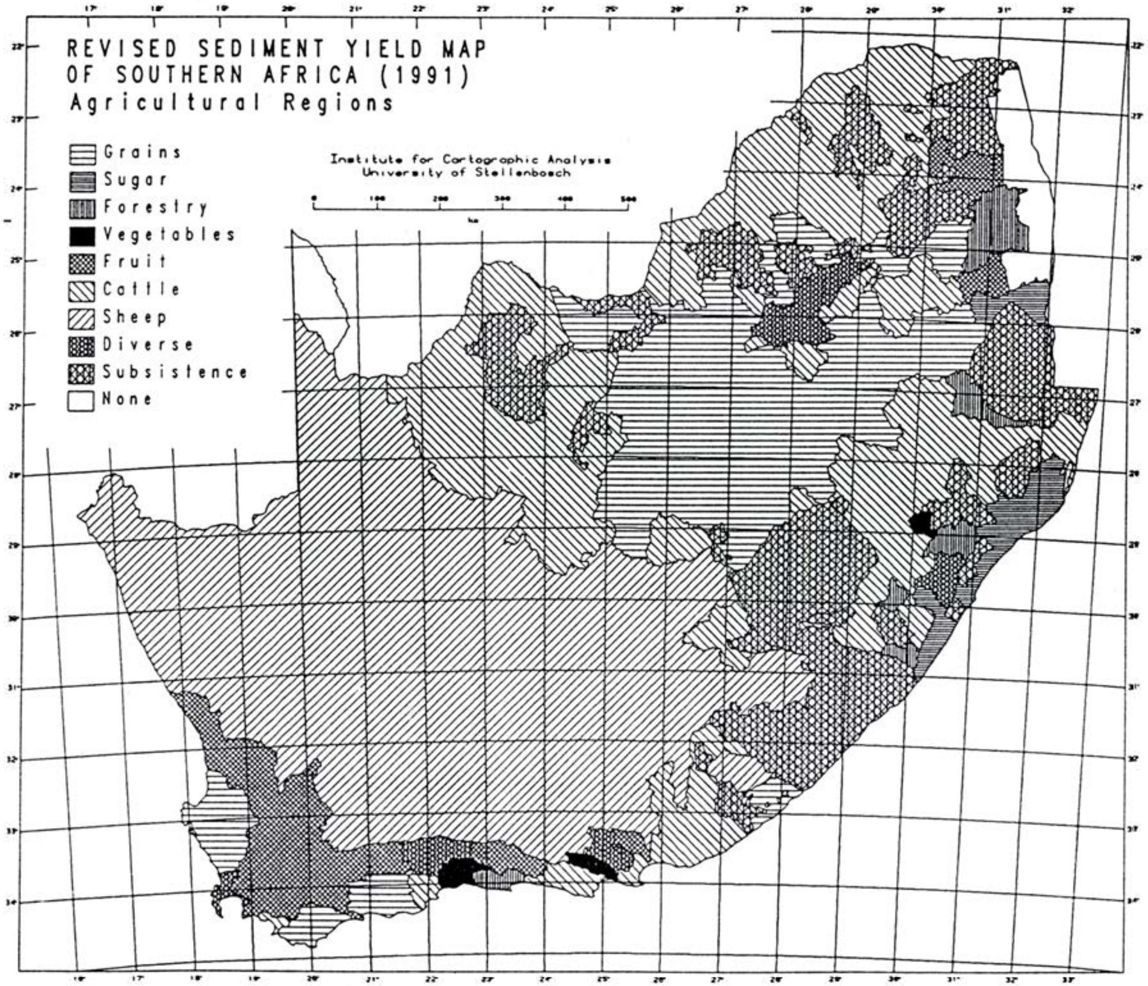
REVISED SEDIMENT YIELD MAP
OF SOUTHERN AFRICA (1991)
Agricultural Regions
Grains
Sugar
Forestry
Vegetables
Fruit
Cattle
Sheep
Diverse
Subsistence
None
Institute for Cartographic Analysis
University of Stellenbosch

FIG. 3

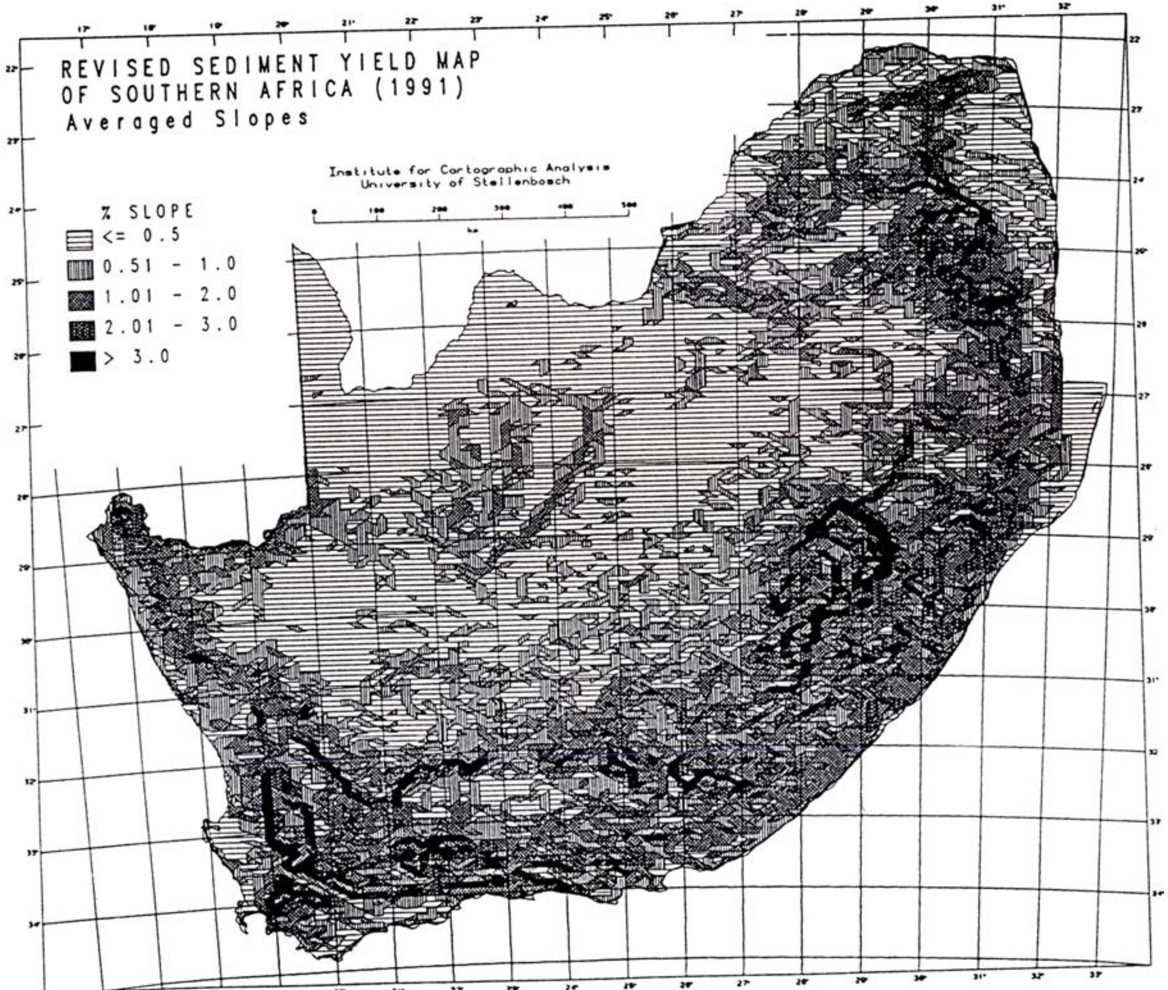
REVISED SEDIMENT YIELD MAP
OF SOUTHERN AFRICA (1991)
Averaged Slopes
Institute for Cartographic Analysis
University of Stellenbosch
% SLOPE
<= 0.5
0.51 - 1.0
1.01 - 2.0
2.01 - 3.0
> 3.0
0
100
200
300
400
500
km

FIG. 4

(c) a stream power equation to represent the sediment transporting capacity of the discharge.

The resulting equations read:

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

and $q = Ci$

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 (Fig. 4)

A is representative of the availability of sediment, B = representative of the sediment carrying capacity and C = runoff coefficient.

Although it is believed that the model provides a good mathematical description of the transport capacity of runoff, it was found impossible to calibrate the model with our data. Once again we have had to come to the conclusion that the availability of sediment and not the carrying capacity of runoff 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 runoff is low to areas where it is high. Thus sediment accumulates in lower-lying areas to be picked up by the first significant runoff. 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 relatively flat, dry areas of southern Africa (North West) where the sediment-carrying capacity of runoff rather than the availability becomes the limiting factor in determining the sediment loads of runoff. These are areas where yields are very low and where little data exists.

SIMPLIFIED STATISTICAL ANALYSIS

Following the disappointing results obtained from comprehensive multiple regression analysis and the clear indications that sediment yields could not be meaningfully linked to runoff 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 uniform yield potential. The regional boundaries (Fig. 6) 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 it's 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 should 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 equal 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. The expected convergence of confidence bands with catchment size is illustrated in Fig. 5. Not all the results displayed the same degree of convergence.

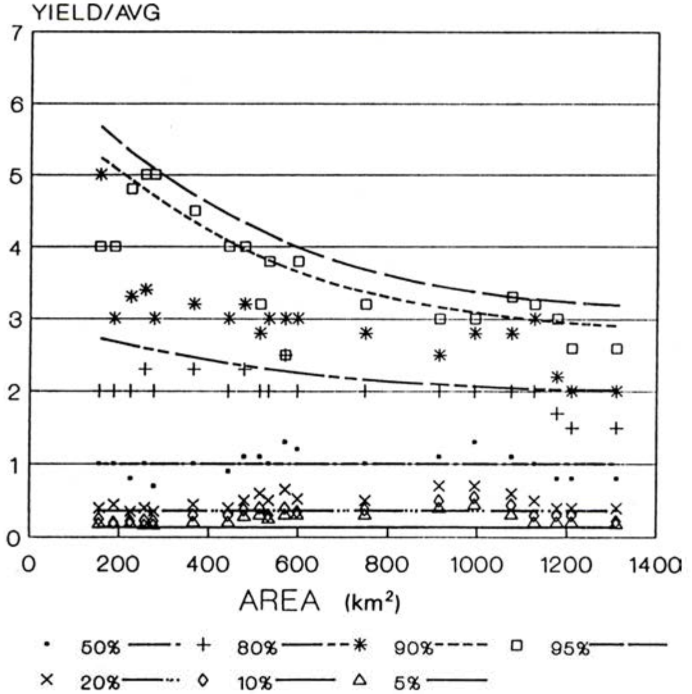

FIG. 5 Sediment yield confidence limits: region 1.

THE NEW MAP AND ITS PRACTICAL APPLICATION

The new map (Fig. 6) can be used in the following way in order to obtain an estimate of the sediment yield of an ungauged catchment. Firstly the region within which the catchment falls is identified and the standardised unit yield values for the sub-regions are

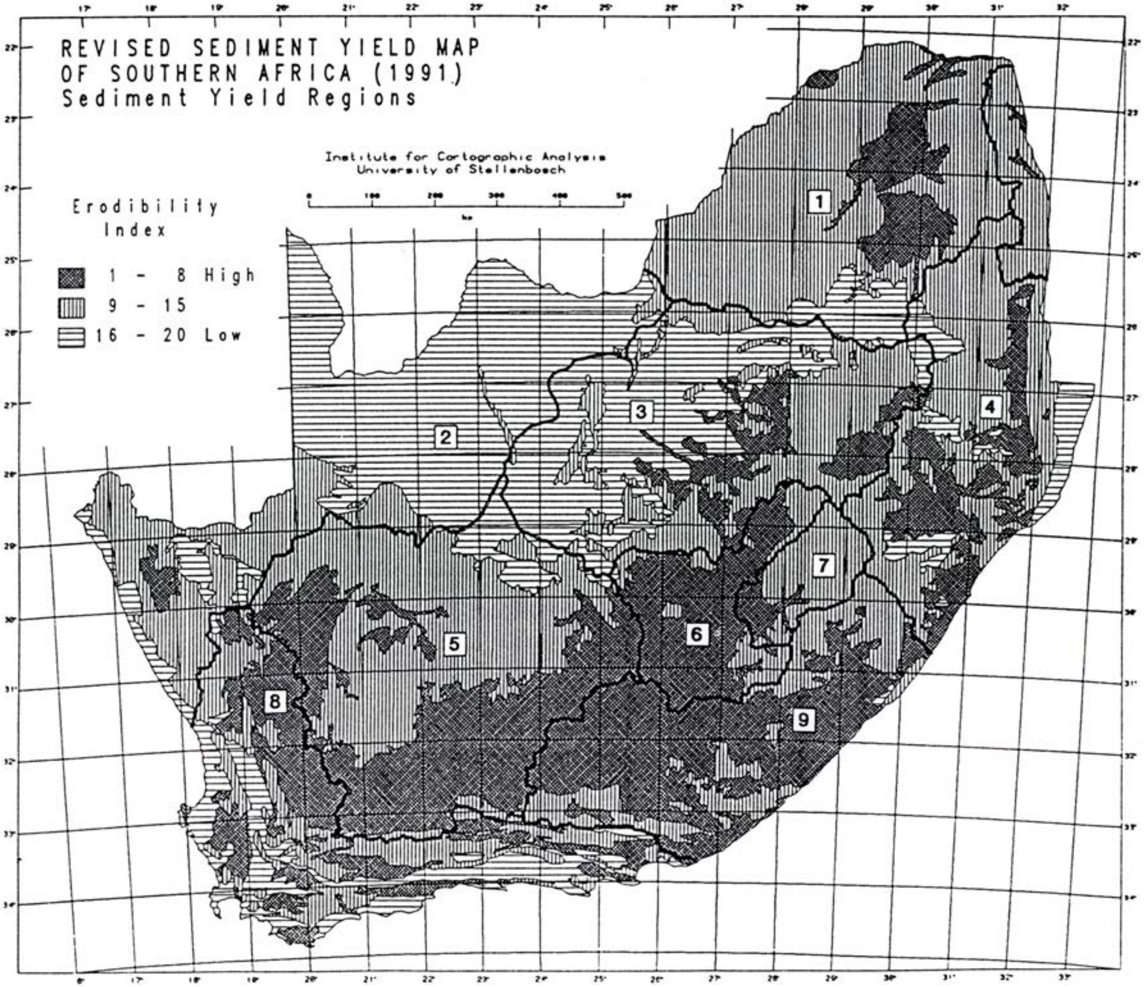
REVISED SEDIMENT YIELD MAP
OF SOUTHERN AFRICA (1991)
Sediment Yield Regions
Institute for Cartographic Analysis
University of Stellenbosch
0 100 200 300 400 500
km
Erodibility Index
1 - 8 High
9 - 15
16 - 20 Low
1
2
3
4
5
6
7
8
9

FIG. 6

then known. The average yield can then be calculated for the catchment according to the proportion of higher, medium and lower sub-regions included in the catchment. By using the appropriate diagram for the region (Fig. 5) an estimate can be made of the expected sediment yield in terms of the size of the catchment and prevailing conditions within the catchment. As it is impossible to define the sediment yield potential of a catchment in absolute terms, experienced judgment has to be involved when maximum or minimum likely yield values have to be estimated.

CONCLUSIONS

The following are some of the conclusions that came out of the study:

(a) Sediment yield values tend to be highly variable and difficult to quantify.

(b) In the southern African context the availability of transportable sediment plays the predominant role in determining sediment yields.

(c) In order to draw generalised conclusions from recorded yield data certain simplyfying assumptions need to be made. We believe that the most fundamental assumption which needs to be made in order to calibrate sediment yield maps is that constant ratios exist between the yields of different supposedly homogeneous areas.

(d) The most important variables in determining average sediment yields for larger catchments are soil types and land condition. Land-use is obviously important, but the same land-use e.g. maize cultivation on different soils in different areas can produce average sediment yields which differ a thousand fold and more.

(e) As may be expected, the variability in yield values decreases with increasing catchment size within a given region.

(f) Other factors which can lead to significantly increased sediment yields, even from larger catchments, include bush fires and urbanisation.

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