Spatial variations in the rate of fluvial erosion (sediment production) over South Africa

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Abstract

The rate of denudation of the past ten to fifty years was calculated from sediment accumulated in man-made reservoirs. The rate of surface lowering generally increases from west to east over the subcontinent. This increase more or less coincides with both an increase in annual precipitation and an increase in the number of storms of high intensity. On the whole there is an increase in relief from west to east, but relief seems to be only a secondary factor in the explanation of denudation rate. No conclusive evidence could be found (from reservoir sedimentation rates) that denudation rates have either decreased or increased over the last ten to fifty years.

Introduction

This study is based on the rate of sedimentation of 87 major storage dams with sedimentation records exceeding 15 years (Department of Water Affairs 1988). The catchments (Fig. 1) cover a 23% "sample" of the total land area of South Africa and represent the main climatic zones fairly adequately. The eroded mass in the reservoirs is not yet lost from the subcontinent, but can be considered as potentially lost. Very little sediment is being stored along river channels since flood plains are extremely narrow or non-existent. It is tentatively assumed therefore that sediment yield to the storage dams over a period of 15 years and longer is more or less equivalent to the material eroded in the catchments. Figures given in this study represent the minimum rates of denudation for the period, since the chemical load and overflow losses are not accounted for.

The first real attempt to map sediment production, which was made by Midgley (1952), was based on rather limited sediment transportation figures (Rooseboom, 1975a). In 1966 Schwartz and Pullen divided the country into several regions according to catchment characteristics and available sediment production figures. Doornkamp and Tyson (1973) drew potential sediment yield maps

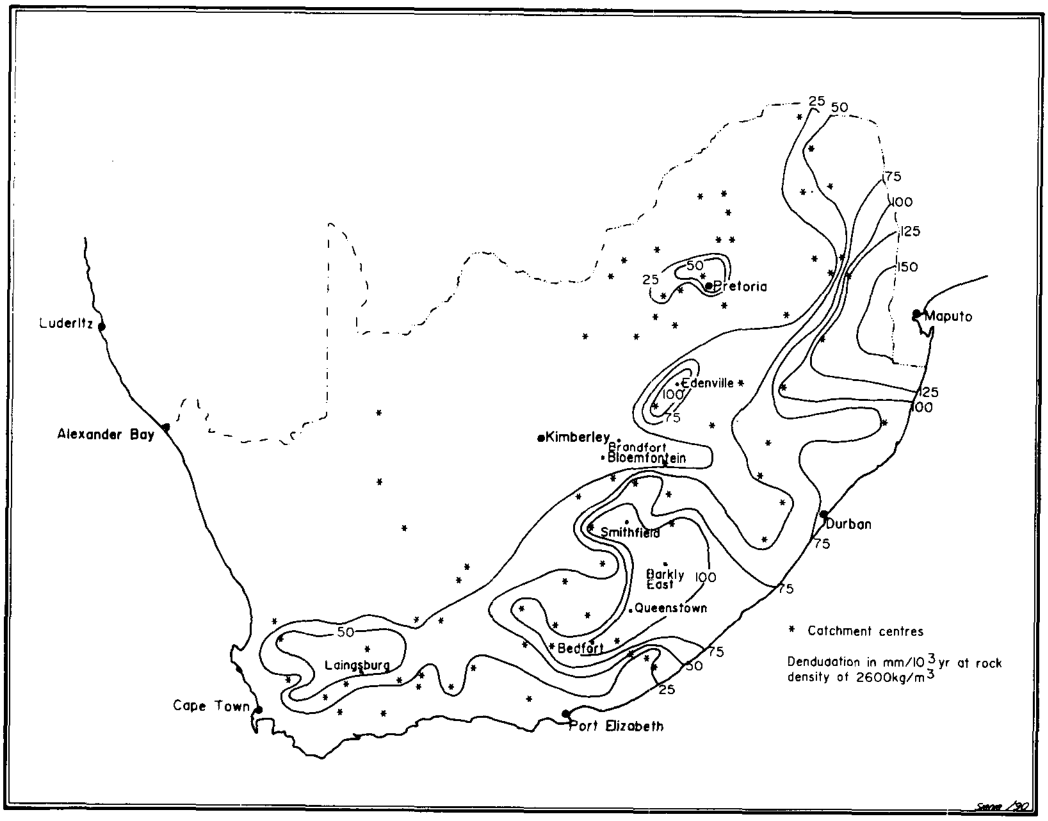

Figure 1
The rate of surface lowering of South Africa as determined from man-made reservoirs.

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(using the Fournier (1960) method) for areas of little and pronounced relief respectively and found that "the areal comparison of estimated yields with Midgley's (1952) observed loads reveals a large measure of agreement." Rooseboom (1975a) mapped sediment production based on sediment accumulation in 50 dams and a few river sediment measuring stations. This map was based on the regional zoning (erodibility map) by HJ von M Harmse (1975, unpublished). Giving the report of 1975 a theoretical base, Rooseboom (1975b) stated that sediment delivery depends on factors such as soil type, vegetation cover, relief, climate and the condition of the catchment. He also found that sediment volume in the Orange River System, as measured at Bethulie, decreased drastically in the sixties and hypothesised that this was probably due to the fact that most of the available soil had already been removed.

Other branches of investigation on erosion in the subcontinent were small catchment and washtrap studies (Chakela, 1980; Le Roux and Roos, 1979; 1982 and 1986), rainfall simulator studies (Smithen, 1982 and 1983; Snyman and Van Rensburg, 1987) and soil erosion modelling (Crosby *et al.* 1981 and 1983; Elwell, 1978; Elwell and Stocking, 1982; Kiggundu, 1985; McPhee and Smithen, 1984; Schulze, 1979 and 1980; Smithen 1980 and 1983; and Smithen and Schulze, 1982). In scope and aim, however, these studies are of only marginal interest to the present investigation.

A few studies on a global scale and of some interest to this study will be referred to briefly. Holeman (1968) reported that "although evidence of excessive erosion in South Africa exists, no quantitative data were located" (p.740-741). Sundborg (1982) stated that man is responsible for more than 50% of the total erosion of land areas and that about 15 000 million to 20 000 million tonnes of solid material are discharged into the oceans annually. This, according to Sundborg, represents only a small part of the total gross erosion from the land surface of the world since most of the sediment is trapped in lakes, reservoirs and on flood plains and other surfaces. According to the global map of Walling and Webb (1983) the annual sediment yield for South Africa ranges from less than 50 t km^{-2} (<20 mm 10^{-3} a at rock density of 2 600 kg m^{-3}) in the west to more than 250 t km^{-2} (<100 mm 10^{-3} a) in the east and 50 to 25 t km^{-2} in the southern Cape Province. Morgan (1986) stated that the major feature revealed by global erosion rates is the vulnerability of the semi-arid and semi-humid areas of the world (Most of the productive areas of South Africa fall in these climates). Comparing river sediment measurements with reservoir sedimentation surveys, Walling (1988) concluded that the latter have several advantages over river measurements; provided the trap efficiency of the reservoir can be estimated and the volumes and densities of the deposited sediment are assessed accurately. Jansson (1988) compiled a map of the "global pattern of variation in net erosion" and found that "part of South Africa and Lesotho have fairly high values, but that in the arid southwest the values are lower" (p. 86).

Determination of the denudation rate

From time to time the major reservoirs are hydrographically surveyed by the Hydrographic Survey Section of the Department of Water Affairs of South Africa. During these surveys storage capacities and the percentage of accumulated sediment are determined from detailed bathymetric surveys. From the changing capacities since the construction of the reservoirs it is possible to determine the rate of sedimentation for different periods in the past. Also listed is the catchment area and other pertinent information such as raising or lowering of the retaining wall and water capacity at full supply level.

To calculate eroded mass, data concerning the density of the sediment are needed. The density depends mainly on the size-frequency distribution of the particles, the extent of exposure to air-drying and the time available for compaction. In a sample of six South African reservoirs Braune (1984) found that sediment densities ranged from 1 060 kg m^{-3} to 1 430 kg m^{-3}. From these an average bulk density of 1 200 kg m^{-3} was calculated. This figure is used in converting volume to sediment mass. For (mostly) submerged sediment this value could be about 10 % too high and for only occasionally submerged sediment about 20 % too low. Bearing in mind that the conditions in most South African reservoirs fall between these extremes the mass estimate of dam sediments using a density of 1 200 kg m^{-3} is unlikely to be incorrect by more that 10 %.

Rock density was arbitrarily taken at 2 600 kg m^{-3}. This "estimate" is based on a previous study (Le Roux and Roos, 1979) in a catchment underlain by rather "young" Post-Cambrian sedimentary rocks and some dolerite where a bulk density of 2 500 kg m^{-3} was calculated. Presumably older rocks and a somewhat greater relative proportion of igneous to sedimentary rocks would yield a higher density. The actual average rock bulk density for South Africa is unlikely to be lower than 2 500 kg m^{-3} or higher than 2 700 kg m^{-3}, the latter figure being the density of the continental siallic shell (Barth 1952). An average density of 2 600 kg m^{-3} is therefore considered realistic.

Surface lowering was calculated as follows:

$$\text{Rate of denudation} = \frac{Vs \times Ds \times 10^3 \text{ m } 10^{-3}\text{a}}{Dr \times T \times A}$$

where:

Vs = Volume of trapped sediment (m^3)
Ds = Density of sediment (1 200 kg m^{-3})
Dr = Rock density (2 600 kg m^{-3})
A = Catchment area (m^2)
T = Period of sediment entrapment (a)

Possible errors in the calculation of surface lowering are the following:

- Exclusion of the chemical load. According to Saunders and Young (1983), working on a world-wide data base, the suspended and dissolved loads are usually of a comparable magnitude. Reliable data for the chemical load are unobtainable and actual denudation rates could be twice as high as the values calculated. However, most of the subcontinent is underlain by sediment and sedimentary rock and most of the dissolved material was probably stored in the interstices of the rock particles and therefore probably does not affect surface lowering to a considerable extent.
- Loss of sediment from reservoirs during overflow. Trap efficiency of reservoirs is usually considered to be a function of reservoir capacity and annual inflow. In a survey of fifteen reservoirs Roberts (1973) found that the amount of sediment lost because of overflow is less than 10 % of the total sediment yield. It is therefore not a major error factor in sediment yield figures.
- Sediment in reservoirs is not actually lost from the subcontinent. Milliman and Meade (1983) warn that calculating surface lowering per unit of time may be misleading because much

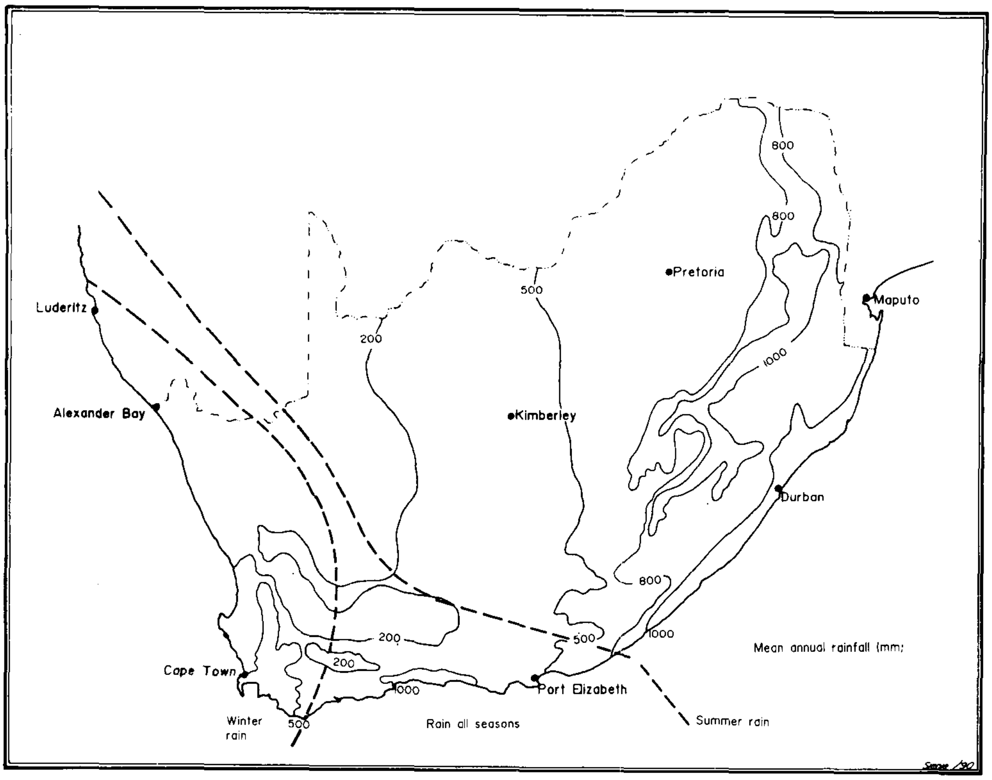

Figure 2
Annual rainfall over South Africa (based on Fig. 3.1 in Matthee and Van Schalkwyk, 1984).

of the material being eroded is not actually lost, but is stored along the river valleys. Trimble (1977) contends that "a steady state wherein net storage approaches zero cannot be justified for much of the humid United States during post-Columbian agricultural occupance". Holeman (1980) found that less than 10 % of the soil eroded from the USA reaches the ocean. This may be true for the USA, but extensive flood plains are all but absent along South African rivers because of recent uplift of the subcontinent. Storage on flood plains and in storage reservoirs is therefore temporary and will be lost in the short to medium term.

- Differences in the time available for sediment accumulation in the different reservoirs. This is to a certain extent similar to the problem climatologists have to contend with. A period of thirty years which (presumably) includes wet (and dry) cycles capable of removing the available sediment may (or may not) solve this problem. Probably different time periods should be used for arid and non-arid catchments. The average accumulation period for the reservoirs used in this study is 25 years and from the climatic point of view the sediment production should be representative.
- Accuracy of the storage capacity surveys by the Department of Water Affairs. The figures supplied by the Department of Water Affairs (July 1988) were accepted as essentially correct for this outline study of erosion rates.

Surface lowering and regional controls

The regional distribution of denudation rates is shown in Fig. 1. The denudation rates as calculated for each of 87 catchments were plotted at the "centre of gravity" of each catchment and isolines of surface lowering ("iso-denudants") were drawn. The regional rate of denudation for most of the western half of the country is less than 25 mm 10^{-3}a. The average rate of denudation for the country (area weighted) is 34 mm 10^{-3} a. High erosion rates are evident in a crescent area stretching from Bedford through Queenstown to Barkly East and from there to Smithfield in the Orange Free State. High erosion rates are also encountered in the north-eastern part of Transvaal. A zone of rather low rates of denudation stretches eastward from Brandfort in a general direction to the south of Durban.

The regional denudational pattern could be caused by one or more of the following factors: rainfall, relief, soil properties, vegetation and land use. The main (active) factor and *sine qua non* for most of the country, is rainfall and related characteristics. This factor and the other, mostly passive, factors will now be discussed.

Rainfall

Langbein and Schumm (1985) found that mean annual precipitation could be used to predict sediment yield from a drainage basin (bearing in mind that the relationship is not a simple one mainly due to the influence of rainfall on vegetation and runoff). They also mention that variations in temperature, rainfall intensity, number of storms and areal distribution of precipitation can affect the yield of sediment. The mean annual isohyets are shown in Fig. 2. As can be seen if Fig. 1 and Fig. 2 are compared, there is, in general, an increase in the denudation rate with increasing annual precipitation. There are, however, also important differences, e.g. the high precipitation to the south of Durban, but without a par-

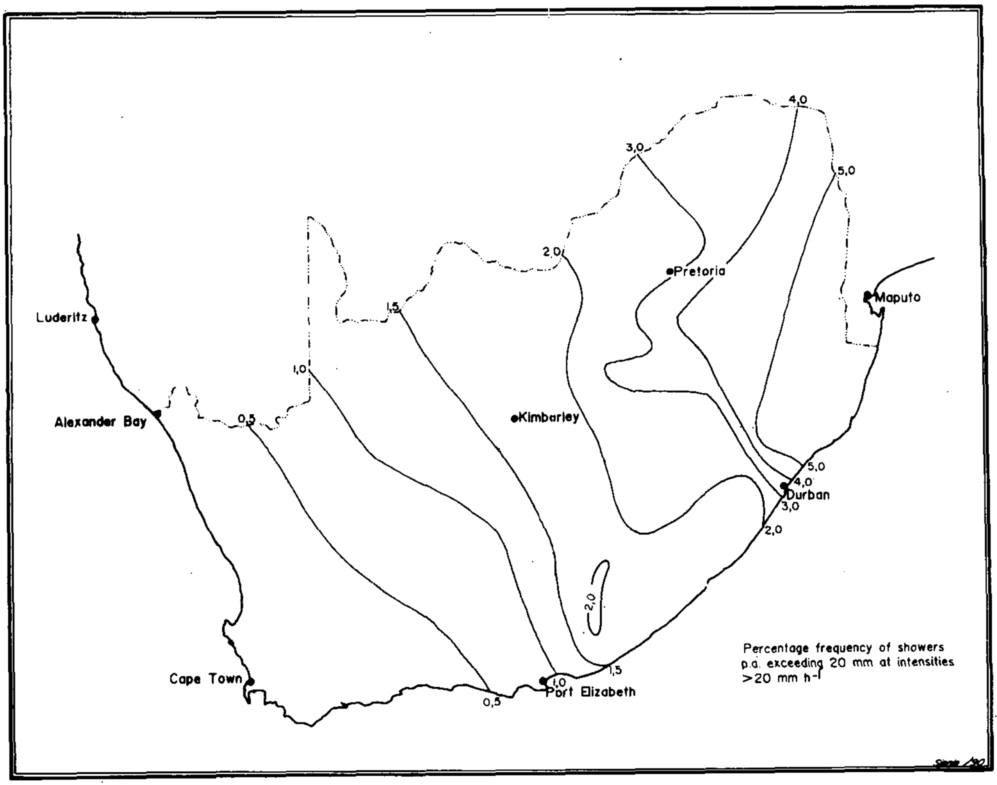

Figure 3
Number of showers per annum exceeding amounts of 20 mm and intensities of 20 mm h^{-1} (isoline values calculated from data in WB 28).

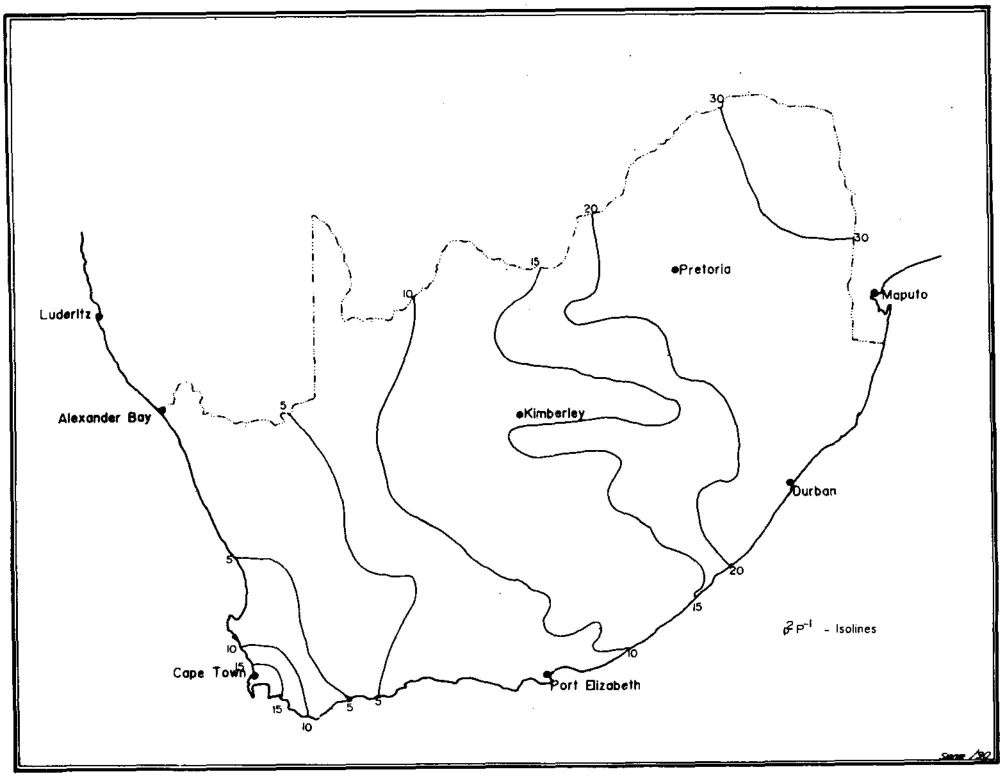

Figure 4
Isolines of $p^2 P^{-1}$, where p = mean precipitation of the wettest month and P = mean annual precipitation (values calculated from data in WB 40).

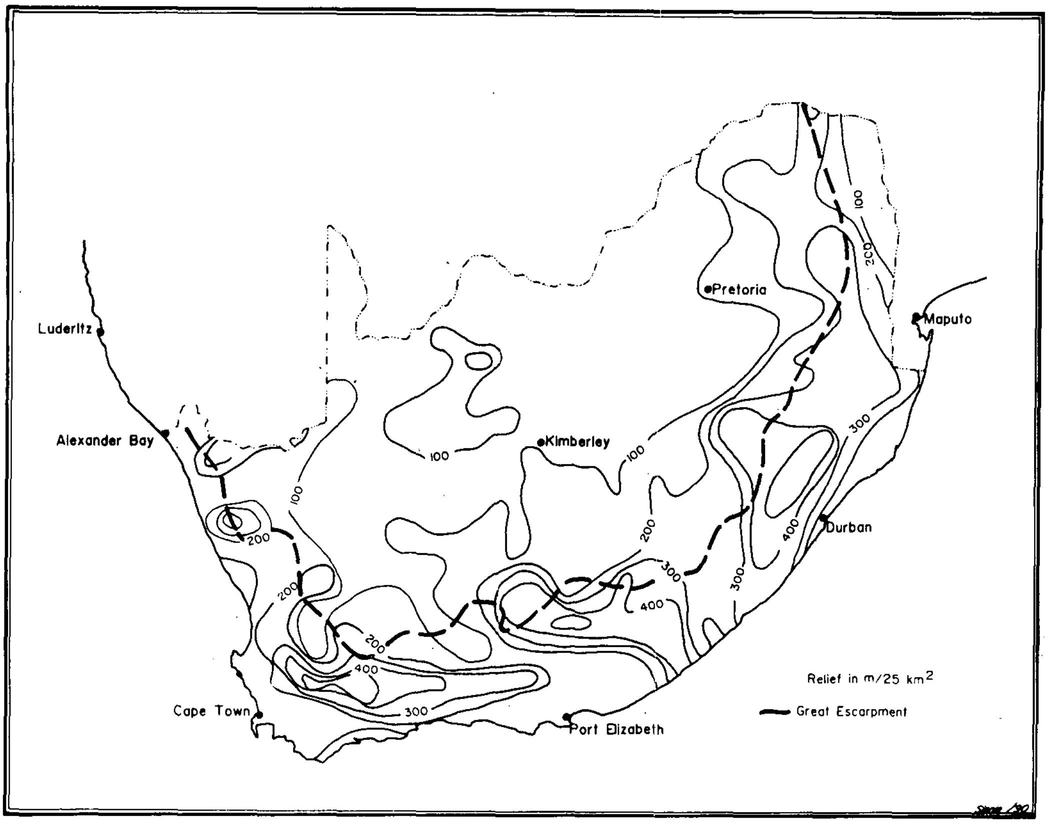

Figure 5
Relief of South Africa in m 25 km^{-2} (calculated from spot elevations and contours on 1:50 000 topographic maps, RSA)

ticularly high sediment yield. A similar lack of correspondence is also evident to the west of Durban where a rainfall exceeding 1 000 mm along the Natal Drakensberg (Great Escarpment) is not accompanied by high erosion rates. The low sediment yields of the area to the immediate east of Cape Town is also "anomalous".

Rainfall intensity and kinetic energy are quite widely used as indexes of erosivity, e.g. the EI30 index of Wischmeier and Smith (1985) and the Hudson index (Morgan 1979). However, a map of EI30 isolines drawn by Smithen and Schulze (1982) proved in many respects to be an even worse predictor of sediment yield than annual rainfall. Since it is known that only intense storms produce runoff and erosion (in southern Africa) the Hudson index (KE >25) uses intensities of 25 mm h^{-1} (Morgan 1979). It was found, however, that only very few storms (or substorms) actually reach an intensity of 25 mm h^{-1} or more. For this study only storms exceeding an intensity of 20 mm h^{-1} and an amount of 20 mm were used (Fig. 3, based on WB28 data), since these intensities and amounts almost always produce runoff into rivers. As can be seen, there is some correspondence between this map and the regional distribution of denudation (Fig. 1). In general, however, it is not much of an improvement over annual rainfall as a predictor of denudation rate.

Fournier (1960) found a general relationship between sediment yield and seasonal precipitation ($p^2 P^{-1}$ where p is the mean precipitation of the wettest month and P the mean annual precipitation). The $p^2 P^{-1}$-isolines (Fig. 4), calculated from WB40 data, agree in a general way with the denudation rate isolines (Fig. 1). The increasing $p^2 P^{-1}$ values near Cape Town are, however, not reflected in an increase in the denudation rate.

Relief

The relief in Fig. 5 was determined over unit areas of 25 km^2. Relief exceeding 200 m 25 km^{-2} is mostly confined to a zone which more or less coincides with the Great Escarpment and the Cape Fold Mountains (cf. Fig. 8). A comparison between Fig. 5 and Fig. 1 shows that relief, as employed here, does not explain the regional distribution of denudation adequately.

Soil

The generalised soil map (Fig. 6) shows a diversity of soils. If Fig. 6 is compared with Fig. 1 (denudation rates) no clear trend is noticeable. Soil characteristics may be important in denudation rates locally, but regionally they are of little importance because other factors, such as those already discussed, mask the influence of soil. It is, for instance, known that the solonetzic soils are particularly prone to erosion, but this is not clearly shown by the rates of erosion.

Cultivated land

Fig. 7 gives some indication of the extent of removal of the natural vegetation and of soil disturbance by man. The distribution of natural veld types and the disturbance of the vegetation by grazing and overgrazing are not considered in this study. It is usually assumed that destruction of the natural vegetation increases erosion dramatically. It is clear, however, if Fig. 1 and Fig. 7 are compared, that although there is a general agreement, i.e. an increasing rate of denudation with increasing percentages of cultivated land,

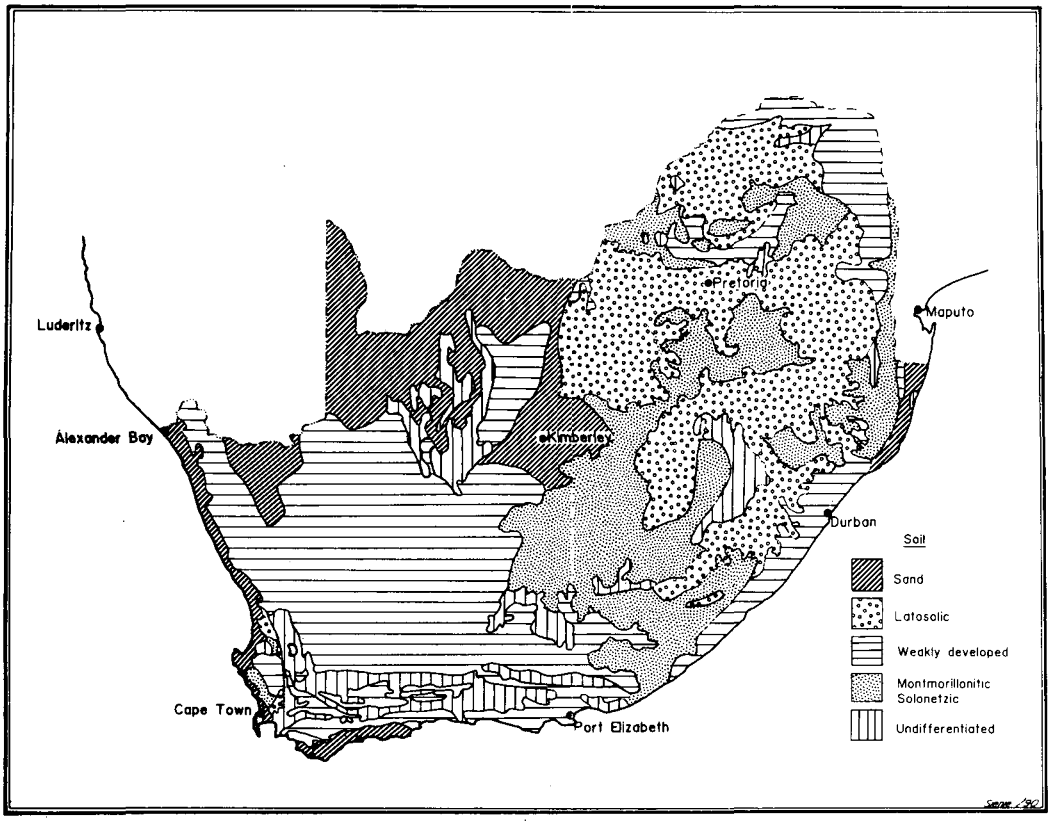

Figure 6
Soil map of South Africa (based on the Soil Map of South Africa, Department of Agricultural Technical Services of the RSA).

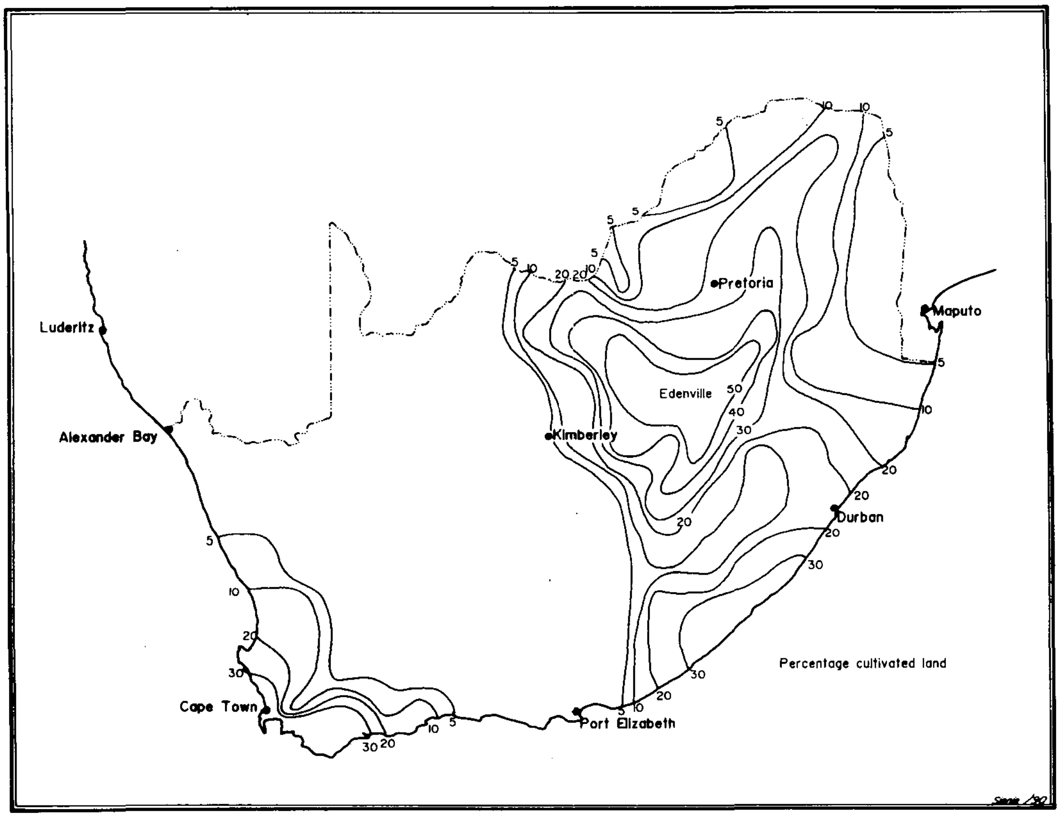

Figure 7
Percentage of cultivated land (values calculated from area measurements on the 1:50 000 topographic maps of the RSA).

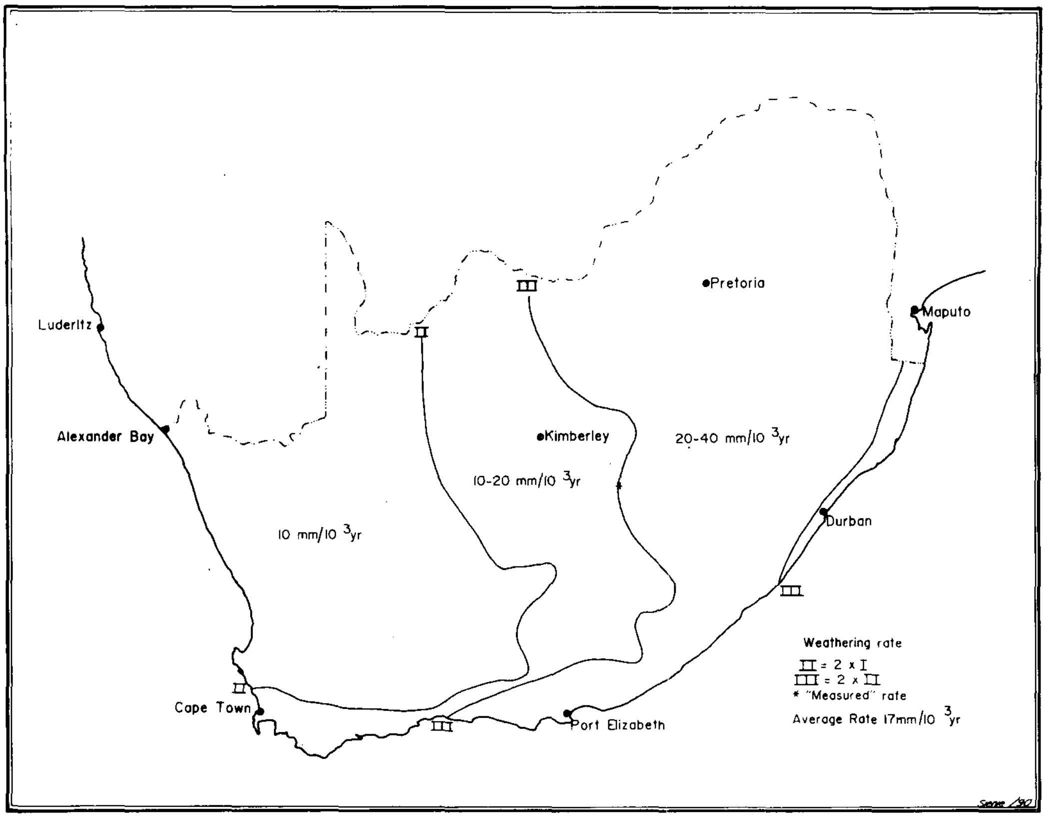

Figure 8
Chemical reaction rate as a possible indication of rate of weathering. Absolute rate of rock weathering in mm $10^{-3}a$ is tentative.

important divergences still occur: in the north-eastern Transvaal (towards Maputo) percentages of cultivated land decrease, but the rate of denudation increases; in the south-western Cape Province an opposite trend (to the former) is noticeable; a considerable area centering on Edenville has cultivated areas exceeding 50 %, but the rate of denudation in this area varies from < 25 to > 100 mm $10^{-3}a$ with an average of (only) 50 mm $10^{-3}a$.

Discussion

The rate of denudation increases from west to east over the central part of the subcontinent. The increase more or less coincides with an increase in annual rainfall, rainfall intensity and the "Fournier index" ($p^2 P^{-1}$).

The low denudation rate in the area near Cape Town is not explained by annual rainfall or the $p^2 P^{-1}$-index. It would appear, however, that a measure of rainfall and rainfall intensity (Fig. 3) does explain erosion rate better in the Cape Town area. The reason why annual rainfall does not explain denudation adequately in this area is probably related to the fact that this is a winter rainfall area receiving only falls of low intensity.

The high relief of the western and southern parts of the region is accompanied by low denudation rates. For the western parts this is not surprising because of the very low annual rainfall.

The low rainfall in the southern parts coincides with the rather low intensities of the winter rainfall region and all-season rainfall regions (Fig. 2). A zone of low erosion rate actually stretches from east of Kimberley in the general direction of Durban (Fig. 1) across different soil types, high relief and rainfall. Interestingly this "anomalous" distribution is only "explained" (partly) by the $p^2 P^{-1}$-isolines. An in-depth analysis of this relationship ($p^2 P^{-1}$ to rate of denudation) will be needed to establish the value of $p^2 P^{-1}$ for the "explanation" of erosion rates.

The observation by Rooseboom and Maas (1974) and Rooseboom (1975) that the sediment volume in the Orange River System decreased drastically from the thirties onward, is not reflected by the rate of sedimentation of dams with long records and repeated capacity surveys (n = 27) in both the Orange River catchment and elsewhere (Table 1). The statistics for these reservoirs (Department of Water Affairs, 1988) show in fact that fourteen dams recorded increases, ten decreases, two a decrease followed by an increase (1 in the Orange) and one an increase followed by a decrease (Orange). These differences could be ascribed to several possible factors, e.g.:

- Differences in the amount and characteristics of the rainfall during the period. This is unlikely because of the rather long periods concerned (Table 1).
- Changing agricultural practices and farm management in the catchments concerned.
- Exceedance of erosional thresholds (Schumm, 1977) in the catchments showing increases in sediment production.
- Progressive loss of erodible soil. This hypothesis was proposed by Rooseboom (1978) and Rooseboom and Harmse (1979) to account for the diminishing sediment loads in the Orange River System. The sedimentation rates of the catchments with long-term records do not support this hypothesis, since five reservoirs in the Orange River recorded increases, four decreases, one an increase followed by a decrease and one a decrease followed by an increase. The decrease at Buchuberg

TABLE 1
ANNUAL SEDIMENT PRODUCTION IN PERIODS FOR DAMS WITH LONG RECORDS (COMPUTED FROM FIGURES IN DEPARTMENT OF WATER AFFAIRS' LIST OF RESERVOIRS, 1988.)

Dam	Drainage system	Period	Sediment deposited*	Decrease (D) or increase (I)
Armenia	Leeu	1951-1974	9	
	(Orange)	1974-1987	26	I
Bellair	Brak	1920-1946	10	
		1946-1981	19	I
Bethulie	Bethulie	1921-1949	66	
	(Orange)	1949-1979	90	I
Bon Accord	Apies	1937-1956	48	
		1956-1980	67	I
Buchuberg	Orange	1931-1959	484	
		1959-1983	30	D
Clanwilliam	Olifants	1935-1948	190	
		1948-1962	203	I
		1969-1980	355	I
Floriskraal	Buffels	1957-1969	378	
		1969-1981	912	I
Grassridge	Groot Brak	1924-1946	1166	
		1948-1966	137	D
		1966-1984	490	I
Kalkfontein	Kamanassie	1923-1955	55	
		1955-1981	72	I
Kamanassie	Riet	1938-1959	862	
	(Orange)	1959-1979	904	I
Kommandodrift	Tarka	1956-1966	566	
		1966-1985	474	D
Koppies	Renoster	1925-1946	357	
	(Orange)	1955-1966	118	D
		1969-1978	736	I
Laing	Buffalo	1950-1968	41	
		1968-1981	74	I
Lake Arthur	Tarka	1924-1935	3071	
		1945-1958	958	D
		1958-1985	102	D
Loskop	Olifants	1939-1966	56	
		1966-1977	884	I
Mentz	Sundays	1935-1946	2418	
		1952-1966	1743	D
		1966-1978	1153	D
Nzhelele	Nzhelele	1948-1966	158	
		1968-1979	87	D
Olifantsnek	Hex	1928-1952	58	
		1952-1962	10	D

Oukloof	Cordiers	1929-1949	4	
		1949-1969	6	I
		1970-1984	7	I
Prins River	Prins River	1916-1939	61	
		1939-1949	67	I
		1962-1981	95	I
Roodepoort	Leeuspruit	1896-1959	11,6	
	(Orange)	1959-1968	12,4	I
		1968-1978	10,4	D
Rooiberg	Hartbees	1949-1962	191	
	(Orange)	1962-1983	37	D
Schweizer-Reneke	Harts	1934-1956	27	
	(Orange)	1957-1979	39	I
Tygerpoort	Kaffir	1922-1938	187	
	(Orange)	1938-1979	26	D
Vaal	Vaal	1956-1965	6716	
	(Orange)	1965-1978	603	D
Van Ryneveld Pass	Sundays	1925-1946	763	
		1946-1966	485	D
		1966-1978	473	D
Victoria West	Dorp	1924-1936	4	
		1936-1954	22	I

* x 10^3 m^3 a^{-1}

since 1959 can be adequately explained by the contruction of the major reservoirs (Hendrik Verwoerd and P K le Roux).

According to Rooseboom and Maas (1974) the net annual sediment yield of the Orange River System at the lowest measuring station (Upington) diminished from 311 t km^{-2} in the early thirties to 119 t km^{-2} in the late sixties. Since the construction of two large storage dams (and possibly other factors), the yield diminished to only about 17 x 10^6 t km^{-2} a^{-1} (Milliman and Meade, 1983) from a drainage area of 1,02 x 10^6 km^2. The Limpopo System yields 33 x 10^6 t km^{-2} a^{-1} (drainage area 0,41 x 10^6 km^2). Assuming that the figures are correct, the subcontinent is lowered in terms of real soil lost terms (using only particulate matter) by about 7 mm in the central and western parts, to more than 30 mm per thousand years (at rock density of 2 600 kg m^{-3}) in the north-east. The Tugela River (at Colenso) annually yields 571 t km^{-2} (Rooseboom and Maas, 1974) giving a denudation rate of 220 mm 10^{-3}a.

The absolute rate of erosion (or denudation) is not in fact important to the agriculture of the subcontinent. What is important is the relative rate, i.e. the difference between rate of soil formation (weathering) and the rate of denudation. The only tentative data available gives a figure of about 20 mm of rock weathering (or soil formation) per thousand years in semi-arid central South Africa (Le Roux and Roos, 1982). Murgatroyd (1979), assuming an unrealistic (e.g. De Swardt and Bennet, 1974) flat, almost featureless erosional (Gondwanaland) platform, calculated a possible geologically normal rate of sediment transport from the basin (Tugela) of 16 t km^{-2} a^{-1}, i.e. a rate of soil production of 6 mm 10^{-3} a. If the former figure (by Le Roux and Roos) is incorporated in a map drawn along the lines proposed by Peltier (1981) for the rate of chemical reactions as related to moisture (average annual rainfall Pf) and temperature (mean annual temperature, Tm), then:

$$Rc = Tm\ Pf \text{ (cf. Fig. 8).}$$

This map (Fig. 8), when compared to Fig. 1, seems to indicate that the rate of erosion during the past ten to fifty years is twice to more than three times the rate of soil formation in the agriculturally important areas of the subcontinent.

Conclusions

The following legitimate conclusions can be drawn from this investigation:

- The rate of erosion is probably at least twice to three times or more the rate of replacement by weathering.
- The diminishing rate of sediment yield in the Orange River System is most probably not due to a change in the sediment characteristics of the catchment area since it is not generally reflected by reservoir siltation rates.
- More research is needed in respect of weathering and soil-forming rates in South Africa.
- Detailed information on the chemical load of the major fluvial systems as well as the sources of the solutes is necessary.
- Rate of denudation is mostly a function of rainfall parameters and several passive factors. The influence of soil cultivation and destruction of natural vegetation on regional denudation should be investigated in individual (reservoir) drainage basins.

- This research has shown that some individual reservoirs "registered" highly variable rates of catchment erosion during different periods. It is to be hoped that if the reason(s) for this could be ascertained, guide-lines for sound catchment management could be formulated.
- It is unlikely that a single parameter can be devised which will be able to explain the regional denudation pattern.

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