Siltation and Soil Erosion Survey in Zimbabwe

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ABSTRACT Rampant soil erosion threatens the long term viability of large tracts of land in Zimbabwe. High population densities of up to 70 inhabitants/km^2, combined with an annual growth rate of more than 3% necessitate the development of water resources to allow land use intensification through irrigation. In the light of widespread man-made erosion sedimentation of reservoirs is regarded to be a major threat to such a strategy. In an integrated siltation and soil erosion reconnaissance study sediment yield (SY) figures were obtained through the measurement of sedimentation in 26 reservoirs. Mean SY ranged from 10-710/tonnes/km^2/annum. Interpretation of 1:25 000 air photography of 1981-1983, covering an area of 11.500km/km^2 indicated that about 20% of the land is subject to serious forms of erosion, like rill and gully erosion. The relationship between SY and state of erosion, though positive is still weak. Indications are that the sediment delivery ratio is in the order of 15%.

INTRODUCTION

Background

The commonly held exotic image of Africa as the continent with abundant fertile land has over the last decade rapidly eroded. Africa now stands for rapid land degradation, declining fertility, soil erosion and drought.

Excarcerbated by the colonial land policies, the situation in much of the Communal Lands (C.L.'s) of Zimbabwe reflects ecological crisis. Rapid deforestation and rampant soil erosion, mainly sheet and rill, threaten the medium term (30-50 years) viability of large tracts of land in the C.L.'s. Land use intensification through a.o. irrigation is regarded essential to match the population growth rates of more than 3% from the already very high rural population densities of up to 70 inhabitants/km .

Sedimentation of reservoirs, in the light of man accelerated erosion, is regarded by the Zimbabwean Government a major time bomb under such an irrigation strategy. Within the framework of the development of a National Master Water Plan for Zimbabwe, a reconnaissance study in Siltation and Soil Erosion was carried out (May 1984-January 1985).

Siltation and Soil Erosion Project (SSEP)

Early 1984 Zimbabwe was known internationally as a low SY but a high soil loss country. Chikwanha & Ward (1979) reported SY's of 30-50 tonnes/km^2/annum, where Elwell (1978) typically measured soil losses of 50-80 tonnes/km^2 /annum. Very few studies in reservoir sedimentation had been undertaken leaving much of the debate between hydrologists and agriculturalists without firm ground.

The very low dam levels, as a result of the 3 year drought further stimulated the speedy implementation of a siltation survey in conjunction with an air photo interpretation based Soil Erosion Survey.

The SSEP aimed to:

(a) Quantify the siltation problems in Zimbabwe's C.L.'s

(b) Attempt to establish a quantitative relationship between sediment yield and the degree of soil conservation.

The study was carried out by Interconsult A/S in very close cooperation with staff of the ministries of Agriculture, Natural Resources and Water Development.

SILTATION AND SOIL EROSION PROJECT (SSEP)

The Sample

Support for the implementation of SSEP came from different sides. Those concerned with land degradation had their main interest in the Soil Erosion Survey. Those with their interest in the CLs were interested in the present rate of siltation of the small dams in these CLs. Those whose primary responsibility was "big water", for irrigation, mining and urban purposes, were interested more generally in SY's and the long-term effects on large dams.

The selection of dams and catchments reflected all these interests. The selection was also designed to ensure that information was obtained concerning both good examples (low SY's) and bad examples (high SY's). Finally the selection of catchments was to a large extent determined by the methodology of reservoir surveys of older dams.

The technical criteria applied in the selection of dams were as follows:

(a) Storage ratio of dams: larger than 0.2 ensuring by and large a 100% trap efficiency of silt.

(b) Age of dams: preferably built before 1975 allowing silt deposits to be of significant volume as well as to achieve a longer-term average.

(c) Availability of basin maps: dams with reliable original basin maps of sufficiently large scale were given preference.

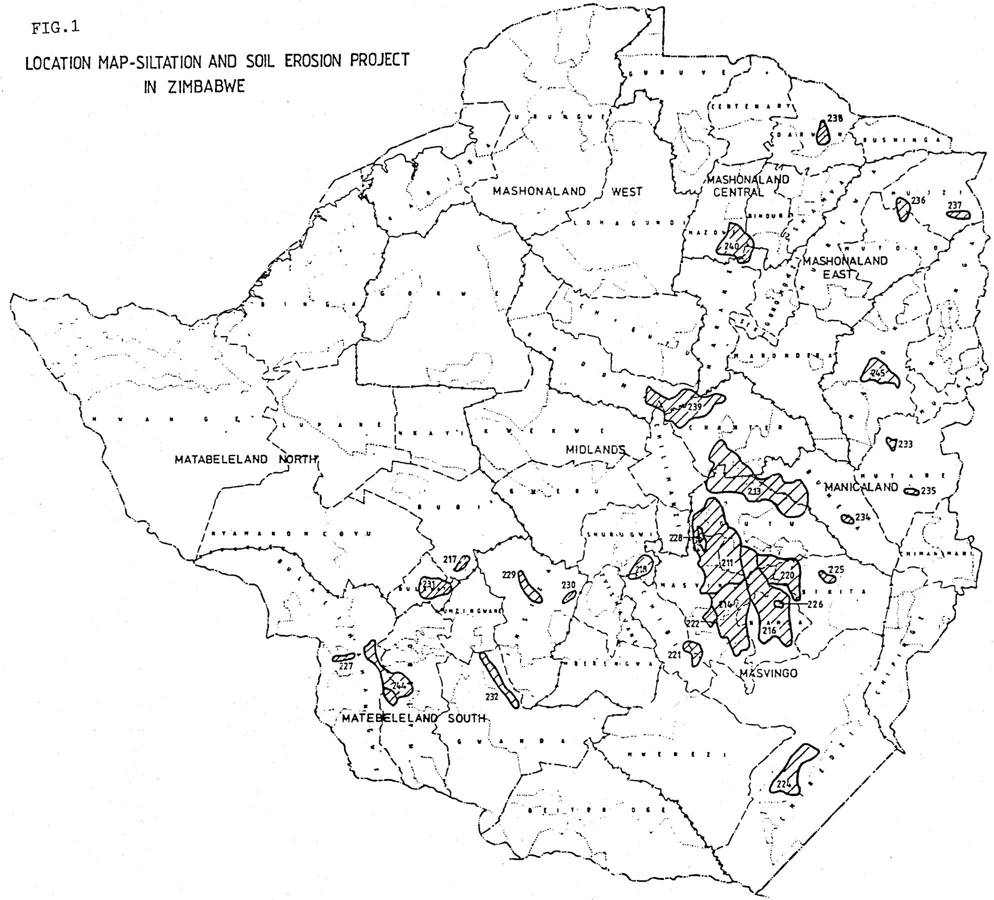
The location of the selected drainage basins is presented in Fig 1. Some key hydrological and drainage basin characteristics are given in Table 2.1 together with the results.

Siltation Survey

Methodology of Siltation Survey Problems of sediment yield assessment have been well described by Walling (1984). Given the reconnaissance nature of this study, combined with the condition that the siltation survey would have to be completed within seven months, all of

FIG.1

LOCATION MAP-SILTATION AND SOIL EROSION PROJECT IN ZIMBABWE



LEGEND

MAP CODE	NAME OF DAM
211	KYLE
212	MANJIRENJI-
213	RUTI
214	BANGALA
216	NYATORE
217	NGWENYA
218	NYARUSHANGE
220	SIYA
221	BANGA
222	MAPANZURE (GOZHO)
224	CHIKWEDZIWA
225	DOWE
226	DEMBA
227	QUESTEDS
228	MAKOHOLI
229	MCHINGWE
230	MABWE-MATEMA
231	UMGUSA
232	MCHABISA-SHEET
233	HAZELDENE
234	CHATIKOBU
235	MASVAURE
236	MASUNZWA
237	NYAMASA
238	NYAMEMBWE
239	NGEZI
240	MAZOWE
245	MWARAZI

REFERENCE

International Boundries

District Boundries

C.L.Boundries

Provincial Boundries

them in the dry season, the method of reservoir survey was adopted to estimate longer term SY.

As many of the dams in the sample had reached record low levels around September - October '84, a combination of survey techniques was used:

a) Conventional air photography controlled by ground control.

b) Echosounding from a survey boat whose position was automatically located from the same ground controls.

c) Direct silt quantity surveys using direct silt depth sounding techniques in the field.

The establishment of ground control, air photography and processing was completed in a major field operation in the most remote parts of Zimbabwe by mid-October, just before the start of the rainy season.

The echosounding survey, using a multi-frequency echosounder and a computerized navigation system, was applied for the first time in Zimbabwe. Despite its high-tech character the technique proved to be highly efficient and successful.

For many of the small dams, built in the 1950's and 1960's, no original reservoir surveys were available. In those cases direct silt depth measurements were made along the range lines as described by Gottschalk (1951). Where the dam was dry, direct silt depth measurements were made by digging observation pits. Where surface or groundwater prevented this direct observation penetrometer readings were taken, backed up by the taking of undisturbed underwater samples with the use of a suction auger.

From the comparison between the old and the new stage-capacity curves the capacity loss due to sedimentation was derived. In case of the small dams, silt quantities were directly derived from the field measurements.

Mean annual SY was then calculated by:

$$\text{Mean Annual SY} = \frac{\text{Sediment Deposited in tonnes}}{\text{area of basin in km}^2 \times \text{age of dam in years} \times \text{trap efficiency}}$$

To estimate trap efficiency Brune Curves were used.

Results of Siltation Survey Results of the Siltation Survey are presented in Table 2.1. Rates of SY, as given in column 8 reflect a wide diversity of rates. On the extreme low side, Makaholi basin yielded only 10 tonnes/km^2/annum. On the upper side in Chibi CL, Nyarushangwe dam received annually 704 tonnes from each km^2 of its badly eroding basin, i.e. more than 70 times as much as Makaholi.

About half of the basins observed yielded less than 100 tonnes/km^2/annum, the other half yielded more. Rates of more than 1000 tonnes/km^2/annum have not been observed in Zimbabwe, unlike parts of South Africa and North Africa.

TABLE 2.1 RESULTS OF SILTATION SURVEY (SSEP)

1	2	3	4	5	6	7	8	9	10
Name of the Dam	Catchment in km^2	Mean Annual Runoff in mm	Storage Ratio CV	Slope in °	Mean Annual Rainfall in mm	Runoff Coefficient in % (3) (6)	Mean Sediment Yield tonnes/ km^2/annum	ppm	Year Built
Kyle	3989	120	3.8	1.5	700	19	60	500	1961
Manjirenji	1536	107	1.7	7	820	13	319	2980	1966
Ruti	2615	143	0.6	3	720	12.5	333	2330	1976
Bangala	1839	222	0.5	7.5	830	26.7	232	1045	1963
Ngwenya	54	36		2	840	6	245	6805	1952
Nyaru Shangwe	108	40	1.2	3	600	3.3	704	1000	1973
Siya	518	335	4.1	9	780	42.9	300	5900	1977
Banga	38	30	0.8	7	770	4	12	360	1972
Mapanzure	43	100	0.3	9	890	12	526	5300	1975
Chikwedziwa	205	12	0.3	1	500	2.4	45	3777	1950
Dowe	52	50	0.1	10	640	8	306	6120	1956
Demba	10	107	0.4	7	600	18	332	6400	1954
Makaholi	154	282	0.9	1.5	650	43.4	10	35	1970
Mchingwe	298	35	0.1	4	630	6	35	1000	1967
Mabgwe Matema	28	60	1.4	5	610	10	80	1300	1969
Upper Umgusa 1)	401	33	0.8	1.5	600	6	48	1450	1946
Hazeldene	59	70	0.8	6	750	9.3	91	1300	1971
Chatikobu	2.4	50	0.4	4	560	4.5	421	8420	1957
Masvaure	8.6	50	0.3	7	650	4	469	9380	1944
Masunswa	29	60	0.7	10.5	700	9	348	5800	1974
Nyamasa	7.1	70	0.5	5	640	11	157	2240	1965
Nyamembwe	7.0	130	0.2	4.5	750	17	410	3200	1958
Questeds 1)	61.4	44	0.3	2	550	8	84	1910	1941
Mchabisa Sheet 1)	435	60	0.03	6.5	600	10	88	1470	1942
Ngezi	1399	70	0.3	1	730	9.6	65	930	1944
Mazoe	348	104	1.1	6	900	11.6	64	490	1920
Mwarazi 2)	283	163	0.2	5	850	19.2	-	-	1961
Antelope 2)	735	65	0.4	4.5	500	43	-	-	1971

1) No Erosion survey carried out. 2) No Siltation survey carried out

Sediment yields found under SSEP seem to be fairly well in line with previous findings. It confirms the extremely low SY's from the highveld, as already found by Chikwanha and Ward (1979). Equally it confirms the high rates in the middleveld as predicted by Kabell (1984). In this sense, SSEP has had a confirmative character.

At the regional level, it would appear that top SY's in Zimbabwe are less than those found in South Africa. However on average SY in the middleveld is comparable with those of the South African middleveld. Therefore it is suggested that the SY map of Africa presented by Walling (1984) be modified by linking the two medium yielding areas in East and South Africa with a band through Zimbabwe.

State of Erosion Survey

It has been one of the implicit aims of the SSEP to shed light on the remarkably unexplored relationship between soil erosion and SY. The siltation study described before was consequently matched with a soil erosion study of the catchment area above the dams. The results of this erosion survey could thus be compared with SY findings from the siltation study.

Methodology of Erosion Survey In order to evaluate the state of soil erosion at the river catchment level, SSEP essentially adopted the soil erosion classification proposed by Ivy (1979) based on airphoto interpretation with slight modifications.

The soil erosion classification is thus based on:

(a) Full coverage of relevant catchment areas.

(b) Ability to observe soil erosion features by means of stereoscope under a 4x enlargement from 1:25 000 air photography.

(c) The most up to date 1:25 000 air photography available.

Seven classes were identified.

Table 2.2 Soil Erosion Classes SSEP

Class	Description of Soil Erosion Features
I	No apparent erosion
II/S	Slight sheet erosion
II/SR	Slight sheet and rill erosion
III/SR	Moderate sheet and rill erosion
III/RG	Moderate rill and gully erosion
III/D	Erosion along drainage lines
IV	Severe erosion

After classification, photographs were then used to prepare soil erosion maps for each of the basins. For the larger basins, the scale of these soil erosion maps was 1:50 000, compatible with ordinary 1:50 000 map sheets. For the smaller basins the soil erosion maps were drawn on a scale of 1:25 000. Through planimetering, the area for each of these classes in a particular basin was determined.

Though the applied method of photointerpretation still contained a substantial subjective element, the method was useful as it enabled officers of the Department of Natural Resources and the Agricultural Extension Service to identify "bad spots". In fact most of the interpretation work was undertaken by these officers, who now apply this method in their work. However, in order to link the State of Conservation to the sediment yield of that catchment and to provide comparibility between catchments, it was necessary to express the general State of Conservation of that catchment in one single figure: the Soil Erosion Index (SEI). In the absence of any other generally accepted soil erosion indicator, the arbitary concept of the SEI was developed. The SEI consists of the weighted average for the state of soil erosion in the catchment. Weights ranged from 0 for Class I to 6 for Class IV.

Results of Soil Erosion Survey Results of the Soil Erosion Survey are given in Table 2.3. In total an area of 11699km or 2.7% of Zimbabwe's land mass has been analysed. A regional assessment of SEI's of the basins reveals high indices in the middleveld and low indices in the highveld and possibly in the lowveld. Typical basins in the middleveld are; Manjirenji with a SEI of 2,8, Nyarushangwe (2.9), Mapanzure (1,5), Demba (2,6), Chatikobu (3,2), Masvaure (2,3), Masunswa, (1,6), and Nyamembwe (1,9). Low soil erosion basins are; Kyle (1,5), Mchingwe (1,3), Mabgwe Matema (1,4), and Mwarazi (0.9). By and large these basins are situated in the highveld, draining commercial farming areas.

Although the 2.7% is by no means a representative sample, as no random sampling was applied, it is nevertheless interesting to look at the aggregate figures at the bottom of Table 2.3.

If one assumes classes III/SR, III/RG and IV to be the areas most in need of drastic rehabilitation then 17% of the areas surveyed would be eligible for serious conservation works such as afforestation, mechanical gully control etc. Classes II/S and II/SR occupy 58% of the sample area. Remedial programmes such as proper cropping and cultivation practices, as well as grazing schemes, could be required in these areas. However, it should be noted that under the 39.2% Class II/S area, large parts could well be used properly. The sensitivity to distinguish heavy sheet erosion from low sheet erosion using airphotography is insufficient to judge good and bad farming practices.

SEDIMENT YIELD AND RESERVOIR YIELD

The effect of sedimentation in a dam is that it reduces the dam's water holding capacity. As dams decline in capacity, their yield is reduced both in quantity and/or in reliability. The relationships between reservoir yields under certain risk levels, storage ratios and the reliability of inflow, have been well established for Zimbabwe by Mitchell (1977). His method of yield prediction for specific reservoirs has been utilized to develop a method to express reservoir yield reduction over time as a function of SY. It is based on the expected reduction over time of the storage capacity of a dam, under different assumptions of SY.

The reduction of storage capacity when the hydrological regime of inflowing rivers remains the same, causes a change of storage ratio. Furthermore, assuming that all sediments are deposited below Full Supply Level (FSL), the ratio between the FSL surface area and the storage capacity increases. As a result evaporation is responsible for increasingly heavier water losses. The

TABLE 2.3 RESULTS OF SOIL EROSION SURVEY (SSEP) (total 11 699km²)

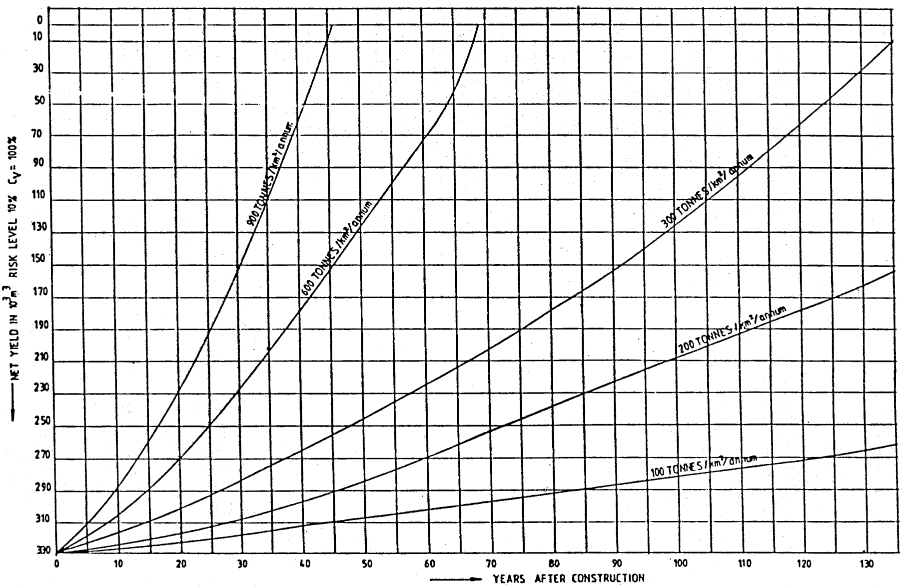
Name of the	Soil Erosion Classification in % of the Catchment														Soil Erosion Index
	I		II/S		II/SR		III/D		III/SR		III/RG		IV		
	%	km²	%	km²	%	km²	%	km²	%	km²	%	km²	%	km²	
Kyle	7.5	288	34.9	1338	31.0	1188	13.0	499	4.2	162	9.1	351	0.3	10	2.0(1.5)[2]
Manjirenji	20.2	307	12.4	188	12.3	187	17.9	272	5.6	85	27.1	409	4.5	68	2.8
Ruti [1]	20.1	36.7	69.7	1275	3.4	63	1.5	28	0.5	9	4.5	81	0.3	5	1.1
Bangala	20.1	367	69.7	1275	3.4	63	1.5	28	0.5	9	4.5	81	0.3	5	1.1
Ngwenya	0	0	26.1	142	35.3	19.2	23.3	12.6	15.3	8.3	0	0	0	0	2.3
Nyaru Shangwe	1.1	11.5	18.5	19.0	20.3	20.9	17.4	17.9	32.0	33.0	10.7	11.0	0	0	2.9
Siya	22.4	116.3	36.0	186.5	13.0	67.3	5.0	25.9	1.0	5.2	23.0	119.1	0	0	2.0
Banga	31.4	12.1	35.9	13.9	19.5	7.5	6.2	2.4	0	0	7.1	2.7	0	0	1.3
Mapanzure	40.5	17.7	12.5	5.5	35.6	15.8	3.4	7.5	0	0	0	0	0	0	1.5
Chikwedziwa	6.0	12.3	72.0	146.9	16.0	32.7	6.0	12.2	0	0	0	0	0	0	1.2
Dowe	42.3	25.5	9.2	5.5	30.3	18.3	14.9	9.0	0	0	3.3	1.9	0	0	1.3
Demba	40.6	4.3	8.2	0.9	0	0	3.4	0.4	0	0	47.7	5.1	0	0	2.6
Makaholi	4.1	6.3	40.1	61.8	35.5	54.7	14.5	22.3	0	0	0	0	0	0	1.7(1.3)[2]
Mchingwe	9.2	27.6	68.5	204.1	11.2	33.3	4.9	14.7	3.2	9.4	3.0	8.9	0	0	1.3
Mabgwe Matema	23.7	6.9	24.9	7.2	41.5	12.0	9.9	2.9	0	0	0	0	0	0	1.4
Upper Umgusa	–	–	–	–	–	–	–	–	–	–	–	–	0	0	–
Hazeldene	48.4	28.8	50.3	29.9	0.6	0.4	0	0	0	0	0.7	0.4	0	0	0.6
Chatikobu	6.3	0.2	0	0	32.9	0.8	0	0	60.8	1.4	0	0	0	0	3.2
Masvaure	0	0	0	0	71.4	6.1	28.6	2.5	0	0	0	0	0	0	2.3
Masunswa	53.6	15.1	0	0	15.9	4.5	7.1	2.0	11.8	3.3	11.6	3.3	0	0	1.6
Nyamasa	0	0	91.6	6.6	8.4	0.6	0	0	0	0	0	0	0	0	1.1
Nyamembwe	22.9	1.9	17.9	1.5	30.3	2.5	7.5	0.6	21.4	1.9	0	0	0	0	1.9
Questeds	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Mchabisa Sheet	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Ngezi	9.1	126.8	51.6	719.3	21.8	303.9	7.9	110.1	4.5	62.7	4.6	64.1	0.5	7.0	1.6(1.4)[2]
Mazoe	25.9	89.1	27.2	93.4	20.6	70.9	16.6	57.1	0	0	9.6	32.9	0.2	0.5	1.7(1.3)[2]
Mwarazi	30.5	86.4	31.0	87.8	5.5	15.6	24.0	68.0	2.6	7.9	3.9	11.0	2.5	6.5	1.6(0.9)[2]
Antelope	3.3	24.0	15.5	113.7	4.8	35.0	19.8	147.1	14.3	105.1	33.7	247.4	8.6	63.1	3.6(3.2)[2]
Average	13.5	1574.8	39.7	4646.8	18.5	2160.0	11.3	1314.2	4.2	494.0	11.5	1349.0	1.4	160.1	2.1(1.9)[3]

1) Air photography classified but not yet analysed 2) Corrected for III/D change of classification
3) Assumed 60% III/D correction

relevant characteristics of the dam can be predicted over time, under different sediment yield assumptions. At any given time the yield from such a reservoir can be calculated with the use of the Mitchell curves. It should be noted that this calculation is based on an equal risk comparison. In practice, water use is not reduced following storage loss in a reservoir. Thus the risks of failure to supply the quantity required is increasing over time, thereby increasing e.g. the risks of mis-harvesting. One example is presented in graphical form in Fig.2. It reflects fairly closely a basin like that of Mapanzure in Masvingo province.

As can be seen from Fig.2, in a dam with an original storage ratio of 0.5, the net yield drops from 330 x $10^3 m^3$ to 180 x 10^3 m at a fixed risk level of 10%, assuming a 600 tonnes/km^2/annum sediment yield, in 40 years. On an annual basis this reflects a yield loss of $\pm 4 \times 10^3 m^3$. Application of the above method for individual reservoirs now enables policy makers to express these costs of sedimentation due to lost income opportunities over time in economic terms. Equally the benefits in terms of reducing SY as a result of basin conservation programmes can now be expressed in additional water supply over time. Given an economic price for water, this can then be expressed in dollar terms.

FIGURE 2

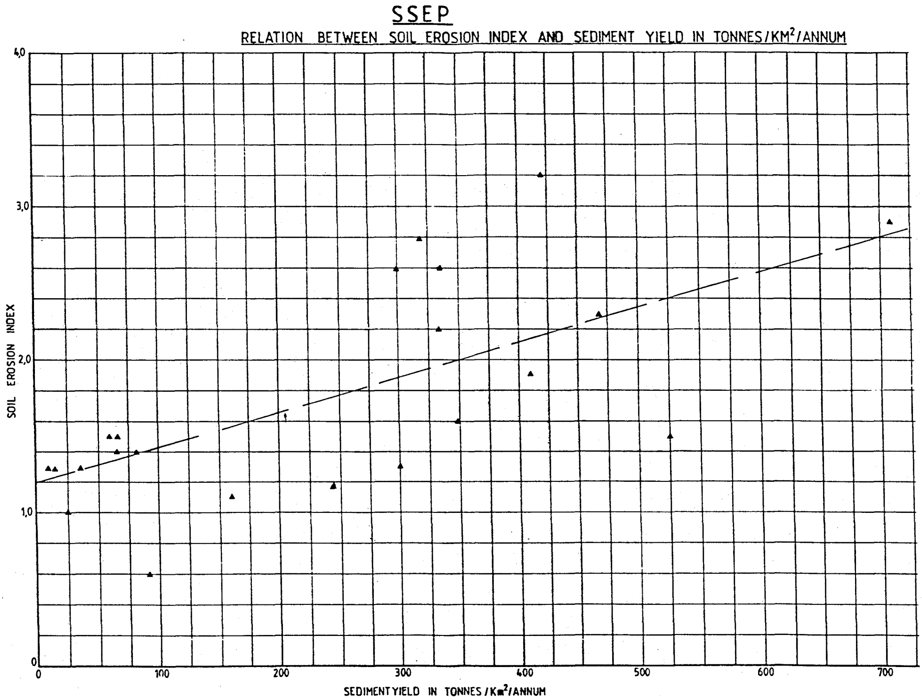


YIELD REDUCTION FOR DIFFERENT SEDIMENT YIELD RATES FOR A DAM WITH ORIGINAL CAPACITY 1.5 mio m^3, A CATCHEMENT AREA OF 30km² AND A MAR OF 100mm.

SEDIMENT YIELD AND EROSION

It has been one of the aims of SSEP to shed light on the relationship between the state of conservation of a basin and SY from that catchment. The relationship established in SSEP is graphically represented in Fig.3. The linear correlation coefficient between the soil erosion index and sediment yield is a positive 0,71. Visual observation of the data however confirms the still very shaky basis of this perceived relationship. The small amount of data, combined with a relatively low correlation coefficient, makes the relationship statistically weak. A broadening of the data base and further statistical analyses are required to gain more insight into this relationship. There remains a major discrepancy between soil losses as predicted by Soil Loss Estimating formula's such as the Soil Loss Estimator for Southern Africa (SLEMSA), developed by Elwell (1978) and Elwell & Stocking (1984) and actually observed SY's. If one uses SLEMSA as a measure to estimate sediment production, the consequent SY's are usually many times more than those observed in the rivers. For instance a typical soil loss of 5 tonnes/ha/annum is largely accepted as the maximum soil loss target. A well conserved drainage basin such as that of the Mazoe dam probably yields not more than 5 tonnes/ha/annum. This is equivalent to a sediment production of 500 tonnes/ha/annum. However, the actual observed sediment yield is only 62 tonnes/km^2/annum, i.e. over a period of 64 years, the sediment delivery ratio

FIGURE 3



could be only 12%. It is clear that widespread, and permanent silt redistribution must have taken place. This ratio between calculated soil loss and sediment quantities observed in river systems, called sediment delivery ratio, is and remains a bone of contention between hydrologists and water engineers on the one hand, and conservationists and agriculturalists on the other. In SSEP no systematic calculation of sediment delivery ratio has been attempted. Further work will be undertaken.

CONCLUDING REMARKS

From a short reconnaissance study as this, the last word on siltation problems and SY's cannot be expected. Neither can this be expected from the relationship between SY and soil erosion in the drainage basins. Other than the limited data base, there are problems in the methodology which necessitate a very careful treatment of the findings.

- Clearly the selection procedure of drainage basins and reservoirs was not done on a random basis. Furthermore given the large number of major variables operative; catchment size, climate, topography, soils, state of erosion, etc., the sample size of 26 was just too small.
- The methodology of comparing reservoir surveys was hampered by relatively small percentages of capacity loss, thus the error introduced due to survey accuracies is substantial.

- The calculation of the SEI is based on a method of air photo interpretation which is not free from subjectivity. Although this method is regarded very useful to identify problem areas within drainage basins, inter drainage basin comparison poses problems. Furthermore the great variation in sheet wash as a result of seasonal cultivation practices cannot be picked up, thus limiting the use of the index as a tool for sediment yield prediction.
- SSEP has compared the SY's over the past 10-20 years with the state of conservation of 1981-1983. The false impression may have been created that under the present state of basin conservation, the prevailing SY's are equal to the mean SY's, thus creating a much too optimistic position. Prevailing SY's or those in the near future may well be much higher, than the mean SY as suggested by Magadza (1984). However, very little is known about the mechanism transforming changes in soil erosion into changes in SY. There is thus a great need to carry out historical studies, using old photography and sediment dating techniques, to shed more light on this relationship.
- Agriculturalists predict a rapid increase of the sediment delivery ratio, as the internal drainage basin trapping capacity fills up. The observation that the sediment delivery ratio is 10-20% is very unsatisfactory. Further research in factors controlling delivery ratio is cruvial in allowing a rational distribution of funds between soil and water conservation programmes.

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