An Assessment of Sediment Loading into an Agricultural Reservoir in a Semi-Arid Region of Kenya

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Abstract

The 95.7 version of Water Erosion Prediction Project (WEPP 95.7) model was applied to an approximately 2.7 km^2 agricultural catchment to estimate the amount of sediment loading into the reservoir of Ndaragwiti Dam, Kenya. The reservoir had 1.9 ha surface area, 1.2 m mean depth and a total volume of 34000 m^3, and was fed by the catchment in a semi-arid region of Lakipia District of Kenya. The catchment was divided into three sub-watersheds based on existing three channels feeding the reservoir. The sub-watersheds were subdivided into 22 hillslopes (plots) according to the slope orientation. Annual sediment that entered the reservoir from each of the sub-watersheds, as well as the sediment that left the reservoir and that retained in the reservoir were generated by the WEPP (95.7) model based on the constructed data sets for the period of 1996. These estimated values were compared with the measured sediment to assess the performance of the WEPP (95.7) model. The estimated annual amount of sediment from each sub-watershed into the reservoir, sediment out of the reservoir through the spillway and the sediment retained in the reservoir ranged between 71% and 75% of the measured values. The WEPP (95.7) model estimated an annual total sediment yield of about 2206 t corresponding to an average sedimentation rate of 817 t km^{-2} yr^{-1}. This estimate is about 71% of the measured rate. The study constitutes a fairly test of WEPP (95.7)'s capabilities since no parameters were calibrated. The findings indicate that the WEPP (95.7) model can reasonably estimate sediment loading when executed without calibration on a catchment devoid of roads in semi-arid region.

Introduction

For many years, governments and individuals have been cooperating to reduce soil erosion and sedimentation on agricultural lands and water bodies (FAO, 1993). Yet much remains to be done as sediment is still the largest single pollutant of streams, lakes and reservoirs. Shahin (1993) noted that the assessment and understanding of erosion and sedimentation processes are essential components of water resource management.

The lower rainfall in semi-arid areas compared to that in humid climates does not imply a corresponding low level of soil erosion by water (FAO, 1987). Semi-arid areas have the potential of generating and transporting large quantities of sediments due to the torrential nature of the rains (Magfed, 1986; FAO, 1987). Almost the total lack of natural protection against detachment of soil due to sparse vegetation especially at the beginning of the rainy season (Pilgrims *et al.*, 1988) and increased biotic interference (FAO, 1973) are responsible for accelerated erosion in the semi-arid areas. The rate at which the process of erosion transport and sediment deposition act are dependent on such variables as rock or soil type, topographic relief, plant cover, climate and landuse (Elwell, 1984).

Sediment production is of great significance to water development because it often reduces the economic life of many reservoirs, thus rendering them inefficient for their initially intended use(s) (Ongwenyi *et al.*, 1993). The design of hydraulic structures requires information on sediment production and loading from the upstream catchment. However, data on sediment production is limited in quantity and quality in Africa (Shahin, 1993), especially in the semi-arid regions of Kenya due to constraints of resources (Sutherland & Bryan, 1986). In Africa, reservoirs are used for water conservation in semi-arid areas (Shahin, 1993). Misjudgement of sediment yield can cause reservoir performance to differ from the design performance (Chin-Lien Yen, 1985).

In the Sipili location of Laikipia District in Rift Valley Province of Kenya where the study took place, underground reservoirs serve as the main source of water for both domestic and livestock use especially during dry seasons. In Sipili, almost all the reservoirs including Ndaragwiti Dam had silted up as at 1994. Had it not been the intervention of the Catholic Parish which desilted some of the reservoirs, the area would have been without water due to financial constraints (Personal communication from the District Water Officer).

Physically-based simulation models of erosion and sedimentation yield require the coordinated use of several submodels (Bogardi *et al.*, 1985). Several simulation models such as the Universal Soil Loss Equation (USLE) (FAO, 1993), Modified Soil Loss Equation (MUSLE) (Renard *et al.*, 1991) and Soil Loss Estimator for Southern Africa (SLEMSA) (Elwell, 1984) are available. However, these models consider only the erosional but not the depositional portion of landscape profiles (FAO, 1993; Renard *et al.*, 1991). Also the practical use of these models are limited due to uncertainties in their input parameters (Bogardi *et al.*, 1985). The Water Erosion Prediction Project (WEPP) model was used for the study because it considers both erosional and depositional portion of landscape profiles, ephemeral gullies within field, complex patterns within field, and the variation of erosion over complex field that vary in topography, soil, cropping and management (Gilley *et al.*, 1988; Foster, 1990; Laflen *et al.*, 1991; FAO, 1993; Flanagan & Livingston, 1995). The WEPP (95.7) model is an upgrade of the empirically–based models expected to replace the Universal Soil Loss Equation (USLE) and the Modified Universal Soil Loss Equation (MUSLE) (Laflen *et al.*, 1991; FAO, 1993; Flanagan & Livingston, 1995). It has been demonstrated to produce reasonable results in south-west Uganda (Biteete–Tukahirwa, 1995).

The objective of the study is to assess sediment loading into a reservoir whose catchment is under agricultural activities in semi-arid region using WEPP (95.7) model. A larger goal of the study is to identify a model that contains empirical parameters to produce a reasonable off-site sediment estimation.

Materials and methods

The reservoir used for the study was Ndaragwiti Dam within the agricultural catchment in the Sipili location of Ng'arua Division, Laikipia District in the Rift Valley Province of Kenya. The study area, which is a semi-arid region, lies along longitude 36.4° E and latitude 0.5° N. The catchment had an area of 2.7 km^2 and lies in the Lower Highland Agro-ecological Zone described as Wheat/Maize-Barley Zone (Jaetzold &

Schmidt, 1983). The parent material of the soil consists of tertiary basic igneous rock deposits on the volcanic foot ridges. Jaetzold and Schmidt (1983) described the soils as well drained, shallow to moderately deep, reddish brown, firm clay with thick humic topsoil, Ortholuvic Phaeozems.

The study method could be put into three parts. In the first part, the catchment was divided into three sub-watersheds (blocks), each feeding each of the three main channels that fed the reservoir with runoff and sediments. The sub-watersheds were subdivided into 22 hillslopes (plots) according to the orientation of each hillslope. The slope length of each hillslope was measured and the steepness determined. The slope length, slope steepness and the widths of the drains along the roads on the catchment as well as the valley which served as channels were also measured. Two types of soil samples were collected from each hillslope (disturbed and undisturbed) for physical and chemical analysis. Three or four representative sampling points in each hillslope were selected. The undisturbed soil samples were collected at these points using three cores each 5.6 cm inside diameter and 4.1 cm long at the centres of 0-10 cm, 10-20 cm and 20-30 cm depths. Similarly, three disturbed soil samples were taken from each layer.

The reservoir was surveyed with grid squares of 15 m by 15 m made over it using ropes. The elevation at each grid on the reservoir embankment was found. The depth of the reservoir at each grid was measured with a long calibrated pole. The original depth at each grid was also measured by driving a calibrated pointed pole through the sediment till there was a sudden increase in penetration resistance thus indicating original bed (Rausch & Heineman, 1984). A contour map of the reservoir was drawn. The present and original volumes of the reservoir were computed using Geographical Information System (GIS) tool of Integrated Land and Water Information System (ILWIS) (GIS by ILWIS, 1994). The volume of the sediment deposition was calculated as the difference of the present and original volumes of the reservoir using the original and present beds respectively as the reference planes. Sediments were collected at the mouth of each of the three main channels and the spillway. Information on management operation in the catchment area and the reservoir was obtained through direct observation and questionnaire administered to farmers.

The second part involved the determination of physical and chemical properties of the soil that were required by the model. The physical properties determined included particle size distribution, gravel concentration, bulk density, saturated hydraulic conductivity and soil water characteristics. The particle size distribution was determined by hydrometer method (IITA, 1979). The gravel concentration was determined by 'wet' sieving as described by Kemper & Rosenau (1986). Bulk density was determined by the core method (Blake & Hartge, 1986). Saturated hydraulic conductivity was measured by the constant head method (Klute & Dirksen, 1986). Soil water characteristics were determined by the pressure chamber method (Klute, 1986). Walkley–Black method as outlined by Nelson & Sommers (1986) was used for the determination of the organic matter. The cation exchange capacity (CEC) was determined by a method described by Udo & Ogunwale (1978).

In addition to the soil parameters

determined in the laboratory, the model required soil erodibility, critical shear stress and soil albedo parameters. These parameters were estimated using formulae documented by Flanagan & Livingston (1995) as follows:

For cropland soils containing 30% or more sand;

$K_I = 2728000 + 192100 * VFS$ ....(1)

$K_r = 0.00197 + 0.00030 * VFS + 0.03868 * Exp.(-1.84 * ORGMAT)$ ....(2)

$\lambda_c = 2.67 + 0.065 * CLAY - 0.058 * VFS$ ....(3)

where, K_I in equation (1) is the interrill erodibility parameter (kg s^{-1} m^{-4}).

VFS in equations (1), (2) and (3) is very fine sand (%) $\leq 40\%$, (if $> 40\%$, use 40 %).

K_r in equation (2) is rill erodibility parameter (s m^{-1}).

ORGMAT in equation (2) is organic matter (%) in the soil surface $> 0.35\%$ (if $< 0.35\%$ use 0.35%).

λ_c in equation (3) is critical shear parameter (N m^{-2}) and in equation (3) CLAY is clay (%) $\leq 40\%$ (if $> 40\%$, use 40%).

For cropland soils containing less than 30 % sand;

$K_I = 605400 - 55130 * CLAY$ ....(4)

$K_r = 0.0069 + 0.134 * Exp. (-0.20 * CLAY)$ . ...(5)

$\lambda_c = 3.5$................................(6)

Where in equations (4) and (5) CLAY $\geq$ 10% (if $<$ 10%, use 10%)

SALB = 0.6/Exp (0.4 * ORGMAT) (7)

where SALB in equation (7) is the soil albedo and ORGMAT is organic matter (%) in the surface soil.

The third part involved climatic data collection. The climatic data of Rumuruti station number 8936064 were collected from Kenya Meteorological Department and the Hydrology Division of the Ministry of Land Reclamation, Regional and Water Development, to supplement each other in terms of data quality. This station was the closest, about 5 km from the study area and with similar climatic condition. Two types of climatic data were collected. The climatic data available was for a period of only 30 years (1967-1996). The mean monthly maximum and minimum temperatures, solar radiation and rainfall were calculated. The rainfall data for the period were analysed to assess the rainfall distribution of the area.

Climatic data for the simulation year, 1996 were used to determine the daily values of rainfall amount, rainfall duration, maximum and minimum temperatures, solar radiation, wind speed, wind direction and dew point as required by the model. The reservoir was desilted in December 1995 and, therefore, it was assumed that the sediment deposit by February 1997 was the effect of 1996 rainfall and hence 1996 was chosen as the simulation year. The basic data on the reservoir as at February 1997 were obtained by survey and shown in Table 1. Some of the original values, however, could be different from the

TABLE 1

Basic data on the reservoir

Name of reservoir	Ndaragwiti
Year of construction	1960's
Year of desilting	1995
Area of catchment (km^2)	2.7
Altitude (a.s.l.) of site (from topo. map) (m)	2020
Assumed level reference bench mark (m)	10
Earth work (m^3)	-
Length of embankment (m)	215
Width of crest of embarkment (m)	2.0
Maximum height of embankment (m)	2.3
Upstream slope of embankment (m)	3:1
Downstream slope of embankment (m)	1.5:1
Maximum depth (m)	2.9
Surface area (ha)	1.9
Length of spillway channel (m)	30
Width of spillway channel (m)	10

values shown since there was rehabilitation the previous year and, therefore, there was the possibility of erosion within the year.

Simulation model

The WEPP (95.7) model is a comprehensive process-based, field-scale simulation model capable of estimating soil loss and sediment yield. The model considers sediment flow from the catchment as well as along well-defined water flow course and estimates both sediment inflow and outflow of a reservoir. Numerous influential processes such as hydrologic, hydraulic, soil (impacts of tillage), erosion processes, plant growth, plant residue and climate for both hillslope and channel as well as impoundment are computed within the model. Flanagan & Livingston (1995) have documented the model and its input data requirements.

The WEPP (95.7) model is run under two categories - Hillslope WEPP (95.7) and Watershed WEPP (95.7) models. The Hillslope model estimates the sediment yield from the hillslope whilst the Watershed estimates the sediment yield from the whole catchment. The Hillslope model requires four input data files for each monitored hillslope. The input files include a climate file, a slope file, a soil file and a plant/management file. The input data for the Watershed model includes the soil loss (output) of the Hillslope model, a channel file and an impoundment file.

The climate file involves two types of climatic data - simulation year(s) data and observed year(s) data. The simulation year data set is the data for the year or years of interest, thus the period within which the sediment is being estimated. These data include daily values of rainfall amount, rainfall intensity, maximum and minimum temperatures, wind speed, wind direction, solar radiation and dew point. The observed data include average monthly values of rainfall amount, maximum and minimum temperatures, and solar radiation for any number of years provided they are available and more than the simulation years.

The slope file comprises slope orientation aspect of the profile, the number of slope points, as well as length and steepness at each slope point from the upper end of the hillslope. The soil file includes number of soil layers, depth of soil layer from the soil surface, and soil properties like interrill and rill erodibilities, critical shear, percentages of sand, clay, organic mater, cation exchange capacity, hydraulic conductivity and gravel concentration.

The plant/management file includes land use, crop types, cropping system, cropping pattern, inter-row distance, inter-crop distance, rooting depth, height of crop at maturity, root to shoot ratio, planting and harvesting time, types of implement used for cultivation, primary tillage depth, secondary tillage depth and number of secondary tillages.

The channel file consists of channel slope data, channel soil data and plant/management data. These data are determined in the same way as hillslope data. The impoundment input file includes bottom width, side slopes and stage of the spillway, size of impoundment, number of stage-area-length points, minimum and maximum stage, and area at which water overflows through the spillway.

The reservoir was fed by only runoff through three channels excavated by the community. For easy running of the watershed model the catchment was divided into three subcatchments with each feeding each of the channels. The watershed model was run three times to estimate sediment loading into the reservoir from the three subcatchments.

Results and discussions

Fig. 1 shows the contour map of the embankment and the bed of the reservoir. The embankment was L-shaped, stretching from the northwest to cover the whole of the south of the reservoir. The reservoir bed was shallow from the northern section of the reservoir and deepened gently towards the southern section. The maximum depth of 2.9 m was found in two pockets enclosed by the contour of 6.3 m. The reservoir deepened sharply just after the middle portion and then rose steeply at the embankment. The depth of the measured sediment deposit ranged from 0.5 m at the northern section where the channels entered the reservoir to 0.01 m at the southern part.

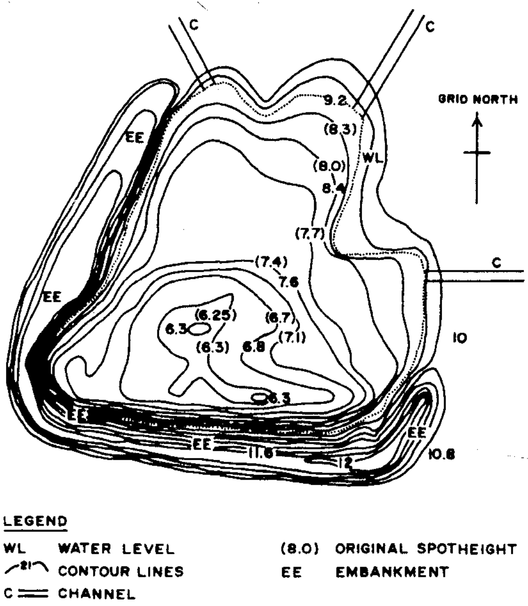

Fig. 1. Contour map of the Ndaragwiti Reservoir

Table 2 shows some properties of the soil on the catchment. The clay content of the soils and the gravel concentration of the catchment increased with depth whilst the sand fraction showed no marked difference. The soils generally showed clayey texture. The hydraulic conductivity, however, decreased with depth. The average organic matter content decreased from 3.7% to 2.7 % with depth. The values of the organic matter content reflected the low fertility of the soil as fertile soils should have organic matter content greater than 6% (Landon, 1991).

Rainfall characteristics of the nearest station of the study area were analysed

TABLE 2

Average values of some soil physical and chemical properties of Ndaragwiti catchment

Depth (cm)	*Parameters*[a]	*Sand %*	*Silt %*	*Clay %*	*Gravel conc. g/100 g*	*Bulk density* mg/m^3	*Hydraulic conduct mm/h*	*Organic matter %*	*CEC Meg/100g*
	$\bar{X}$	26.8	24.5	48.7	2.7	1.23	1.64	3.67	38.1
0-10	σ	5.1	6.2	8.4	2.5	0.16	1.39	0.54	7.7
	CV	18.9	25.4	17.4	92.8	13.30	84.5	14.70	20.3
	$\bar{X}$	26.5	21.9	51.6	4.3	1.26	1.21	3.00	36.4
10-20	σ	5.7	5.1	7.9	3.3	0.14	0.95	1.04	5.3
	CV	21.5	23.3	15.3	77.1	11.03	78.6	34.90	14.5
	$\bar{X}$	26.9	20.9	52.2	5.8	1.26	1.19	2.74	34.0
20-30	σ	5.3	6.1	8.9	4.1	0.13	1.00	0.59	5.6
	CV	19.6	29.2	17.0	71.3	10.30	83.6	21.50	16.2

[a] $\bar{X}$ is the mean of population, σ is the standard deviation, and CV is the coefficient of variation (percent)

extensively. The major force for erosion and sedimentation was by rainfall (Renard, *et al.* 1991). The analysis was conducted on the 30 years (1976-1996) rainfall data. The mean annual rainfall was 701 mm. The year 1977 had the highest total rainfall of 1181.1 mm, followed by 1974 of 1021.1 mm and then 1990 of 1019.2 mm. The least of 410.6 mm total rainfall occurred in 1984. Each of the remaining years had total rainfall less than 900 mm. The rainfall sequence followed a 'zigzag' pattern (Fig. 2) with 12 years below and 10 years above the mean rainfall while the remaining years were almost equal to the mean rainfall. A 'high' rainfall was likely (about 74% probability) to be followed by a 'low' rainfall the following year taking the mean rainfall as a reference.

It was observed that only few months of rainfall in each year brought the rainfall close or far above the mean. In 1996, June, July and August alone contributed 562.5 mm, about 68.4% of the annual rainfall. In 1990, February, March and April contributed 459 mm, 45%. In 1980, May alone contributed 223 mm, 51.3% and in 1977, April, May and November contributed 631 mm, 53.4%. In 1972, June alone contributed 202 mm, 36.6% and in 1967 April, June and August contributed 353.6 mm, 50%. The high variability of the rainfall distribution indicated the erratic nature of the rainfall in the study area. This could contribute to enormous soil erosion and sedimentation even though the area is semi-arid as observed by FAO (1987) and Magfed (1986) in connection with sediment production in relation to rainfall distribution in semi-arid areas.

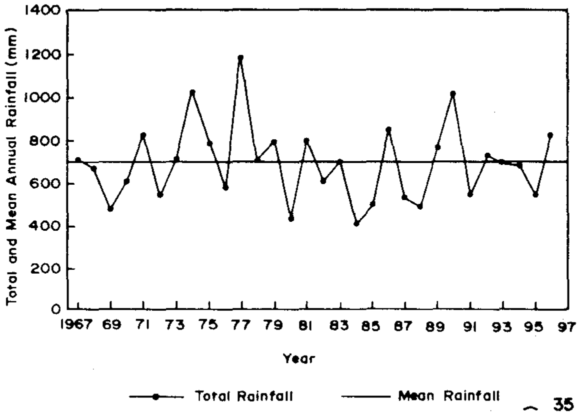

Fig. 2. Annual rainfall variation of Rumuruti

The total present volume of the reservoir was 29,756 m^3 and the original volume was 32,326 m^3 (Fig. 3). Thus the volume of the sediment deposition in the reservoir was 2570 m^3. The average bulk density of the sediment when determined in the laboratory was 1.2 mg m^{-3}. Thus the total sediment deposition was about 3,084 tonnes being the measured sediment. The area of the catchment was 2.7 km^2 and, therefore, the sedimentation rate was approximately 1,142 t/km^2/year. This sediment yield was comparable to the sediment yield of 1,256 t/km^2/year derived from Twake basin between Fourteen Falls and Mavindic gauging station as reported by Muya (1990). The comparison was made because the Twake catchment has farming activities similar to the Ndaragwiti

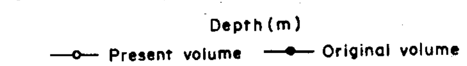

Fig. 3. Cumulative volume-depth relation of the Reservoir

catchment and again both are in semi-arid areas.

Three main channels fed the reservoir from the catchment. The sediment yield was, therefore, assumed to come from three subcatchments - Subwatershed A, Subwatershed B and Subwatershed C. The annual amount of sediment loading into the reservoir from each of the subcatchment, that come out of the reservoir through the spillway and that retained in the reservoir as estimated by the WEPP (95.7) model and their corresponding measured values are shown in Table 3. The estimated total annual sediment loading from Subwatersheds A, B, and C into and out (through spillway) and that retained in the reservoir was approximately 1110.4, 436.9, 892.6, 233.2 and 2206.7 tonnes respectively. These are 73, 75, 72, 72 and 71 percent of the corresponding measured values (Fig. 4). The average sedimentation rate from the catchment was 817.1 t km^{-2} yr^{-1} considering the estimated sediment retained in the reservoir. The model seemed to underestimate the sediment load as clearly shown in Fig. 4.

The differences between the measured and the estimated could be attributed to the following reasons:

(a) The desilting was done manually by the community on individual basis. Therefore, the desilting could not have been done thoroughly leaving some pockets of silts in the reservoir. These silted pockets then leveled on the reservoir bed during the onset of the initial rains.

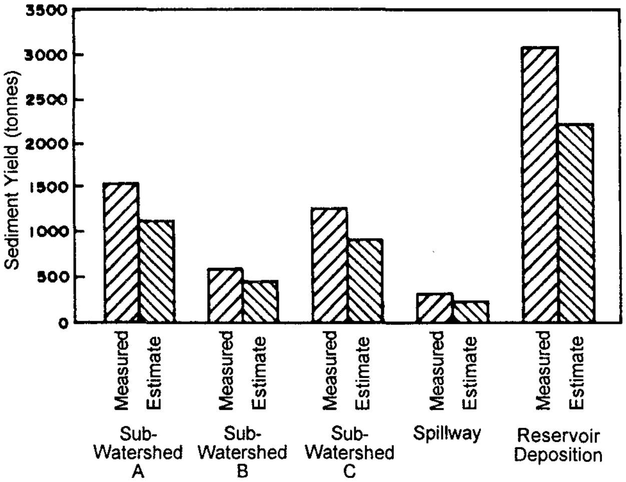

Fig. 4. Comparison of measured and WEPP estimate of sediment yield from the Sub-watersheds, through spillway and reservoir deposition

TABLE 3

Comparison of measured and WEPP estimate of sediment loading from subwatersheds (tonnes)

		Subwatershed A	*Subwatershed B*	*Subwatershed C*	*Total*
Sediment into the reservoir (t)	Measured	1518.8	582.9	1239.9	3341.4
	WEPP estimate	1110.4	436.9	892.6	2439.9
Sediment out of reservoir (t)	Measured	-	-	-	318.5
	WEPP estimate	106.1	42.3	84.8	233.2
Sediment remain in the reservoir	Measured	-	-	-	3084.0
	WEPP estimate	1004.3	394.6	807.8	2206.7

(b) During the desilting of the reservoir, the silt was dumped on the embankment and, therefore, might not have consolidated enough before the onset of the first rains. Part of this silt might have had its way back into the reservoir.
(c) The roads on the catchment were not tarred and, therefore, could contribute a lot of silt into the reservoir. However, the model had no provision for roads.
(d) The site was very windy and dusty especially during dry periods thus contributing to wind erosion. The model did not consider wind erosion.
(e) The pole used for the original depth measurement of the reservoir was pointed and, therefore, there was the possibility that it went beyond the required depth.

The model showed a fair estimate of sedimentation and was very comparable to the sediment yield of 733 t km^{-3} yr^{-1} obtained from Kalundu basin in the Kitui District as reported by Edwards (1977). The Kalundu catchment has farming activities and climatic conditions similar to the Ndaragwiti catchment.

Conclusion

The WEPP (95.7) model was used to assess soil loss from Ndaragwiti catchment, an agricultural land in a semi-arid area, and the sediment deposition in the reservoir was for one year. Within the existing conditions of available data, the model estimate of the sediment load is approximately 70% of the measured. Even though the model underestimated the sediment load, it is considered to be a fair estimate, considering the possible pockets of silts during the manual desilting, the possible unconsolidated embankment of the reservoir after desilting before the onset of the first rains, the wind erosion and the human error in measuring the original depth of the reservoir. All these might have contributed a lot of sediment yield but were not accounted for. It must be concluded that it is worthy to adopt WEPP (95.7) model as a predictor of soil losses from agricultural lands in semi-arid areas and apply it in design, planning and extension in Africa.

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