Seasonal variation of sediment yield on a gentle slope in semi-arid region, Tanzania

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Abstract This research was conducted on a gentle slope in inland area of Tanzania for two years, in order to clarify the seasonal variation of sediment yield on inter-rill area in semi-arid zone. The sediment yield and runoff indicated the clear relationship, except for the value at the beginning of the rainy season. Sediment yield varied seasonally with the amount of erodible soil and vegetation coverage. The comparison of sediment yield at bare land with grassland which grows only during the rainy season suggested the following mechanisms. The decrease in the sediment concentration at the beginning of the rainy season was controlled by the existence of a lot of erodible soil on the ground, and the decrease in it in the late rainy season was controlled by the developing vegetation. The annual sediment yield was estimated from the relationships of sediment yield factors. Soil erosion rate at the complete bare land was 3.1 mm/yr, on the land covered with an acacia tree was 1.0 mm/yr and on the grassland was 1.2 mm/yr.

INTRODUCTION

In recent years, it has been confirmed that sediment yield was most remarkable in semi-arid, seasonal mediterranean, or tropical monsoon conditions (Walling & Webb, 1983). Especially, in semi-arid regions, the soil erosion caused by overland flow is an effective geomorphic agent. The predominant denudation processes in semi-arid zones are rainsplash, sheet erosion and "rain-flow transportation" proposed by Moss *et al.* (1979). Rapp *et al.* (1972), based on air photo interpretation and field checking on Dodoma in Tanzania, made clear that more sediment yield was caused by rainsplash and sheet erosion than by rill erosion. The "rain-flow transportation" is the process that occurs when raindrops impact on the soil surface covered by thin layers of water flowing over it. Moss *et al.* (1979) indicated that the process is especially effective on gentle slopes.

Evans (1980) reviewed about sheet erosion on the inter-rill that the factors controlling the temporal and special variation of erosion are the rainfall, vegetation, soils, and slopes. However, the seasonal variation of sediment yield and its control factors on a gentle slope have not yet been made clear.

The objective of the present research is to confirm the seasonal variation in the sediment yield on the inter-rill areas, to make clear the factors of sediment yield on bare land and land covered with vegetation, and to estimate and forecast the annual soil erosion rates in this area.

EXPERIMENTAL SITE AND METHODS

The experimental site is located on a slope of Makutapora basin, 25 km north of Dodoma, capital of Tanzania. This slope is gentle, about 4 degrees, and its elevation is 1100 m above the sea level (Fig. 1). The basement of this area mainly consists of granitic rocks and a small block of metasediments of Precambrian. The basement is covered with a thin soil layer of about 0.5 m thick. The soil layer consists of reddish silt with granule and the saturated hydraulic conductivity is 10^{-3} cm/s. The specific gravity of the surface soil around this slope is 2.28 to 2.35 (g/cm^3) and the porosity is 31.9 to 38.5%. The climate in this area is a tropical savanna. Most of the annual rainfall, about 550 mm, falls during the rainy season, from December to April.

The measurements of the runoff and sediment yield were conducted at four field plots installed on an inter-rill area. Four field plots are 3.2 m x 3.2 m (10 m^2) in size, and each land surface is managed as follows. The plot P1 is kept bare throughout the year, the plot P2 is covered with an acacia tree of 2.5 m high, and the remaining two, P3 and P4, are left grasses to grow during the rainy season, where P3 was measured in 1990, and P4 in 1991. The measurements were carried out from December to February in 1990, and from December to February in 1991.

The erodible soil amount was estimated from the weight of soil that was able to be collected by sweeping out by a soft brush two small plots of 400 cm^2 (20 x 20 cm). A number of areas were randomly selected on the inter-rill area around this site. The erodible soil amount were measured each 15 days from December to February in 1991. The erodible soil depth (mm) is calculated by dividing the soil amount by a specific gravity and volumetric soil content (%). Vegetation coverage (%) was surveyed from the photo analysis each 2 to 10 days from December to February in 1991.

RESULTS OF FIELD OBSERVATION

Figure 2 shows the variations of the runoff and sediment yield at the field plot P1 from December to February in 1990. From this figure, the characteristics of the runoff and sediment yield on the interrill area are as follows: (1) the runoff relates to the rainfall; (2) in the beginning of the rainy season, sediment yield is high; (3) during the rainy season, sediment yield decreases gradually; and (4) in a heavy rain conditions, the sediment yield is high.

Factors of seasonal variation

In order to confirm the factors that control the variation of sediment yield, the

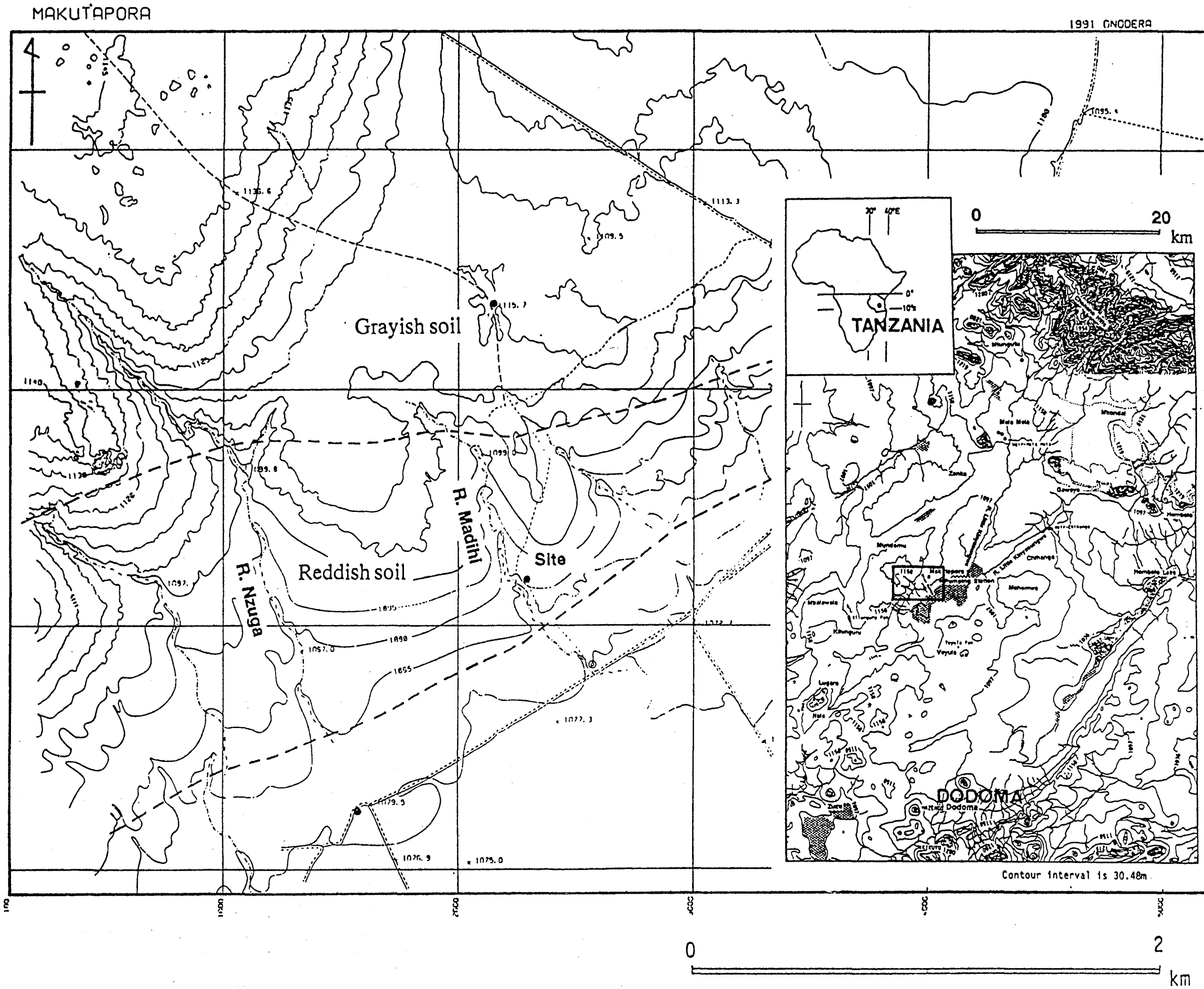

Fig. 1 Location map of the study area.

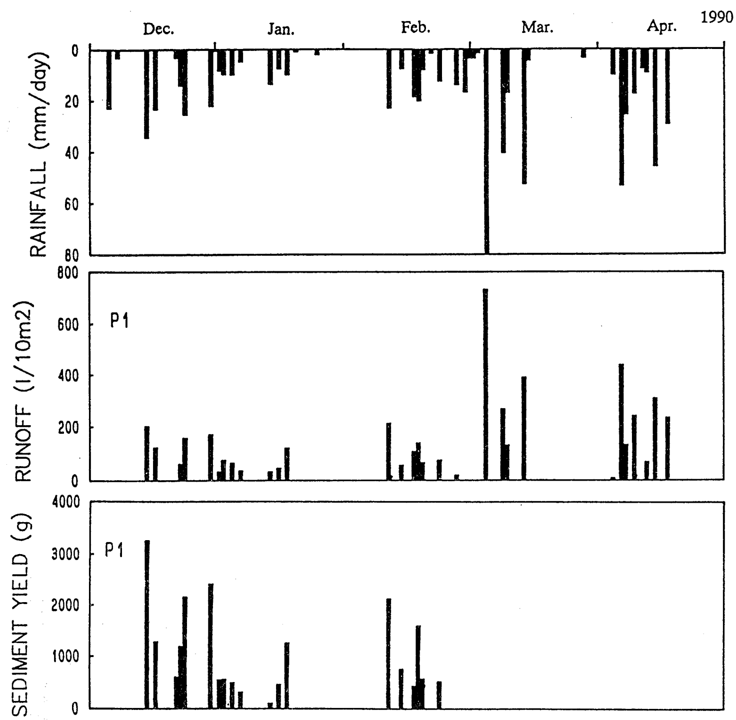

Fig. 2 Variations in the runoff and sediment yield on the bare land, field plot P1, from December, 1989 to April, 1990.

following statistic analysis was carried out. In the present paper, the authors considered the vegetation coverage, existence of the erodible soil and runoff amount as the control factors of variation of soil erosion on the area which have a similar morphology.

The sediment yield is related to the runoff by the following correlation:

$$S = 12.5Q - 99.9 \quad r = 0.88 \text{ at P1} \tag{1}$$

$$S = 17.4Q - 100.9 \quad r = 0.88 \text{ at P3} \tag{2}$$

where S is a sediment yield (g/10m^2), and Q is a runoff amount (l/10m^2).

Other studies (Wischmeier, 1975 and Elwell, 1981) had indicated that sediment yield decrease exponentially with the increasing of a vegetation coverage. The present paper considers not only a vegetation coverage but also the erodible soil amount as one of the seasonal variation factors except for the runoff amount. Figure 3 shows the relationship between time since the first rain event in the rainy season and the sediment concentration at the bare area (P1) in a whole year and the bare area (P3) only along the dry season, where grasses gradually grew during the rainy season. This figure indicates the following variation:

(1) The sediment concentration decreases rapidly at the beginning of the rainy season.
(2) The sediment concentration decreases slowly in the late rainy season.
(3) The sediment concentration at P1 decreases more rapidly than at P3 at the beginning of rainy season.

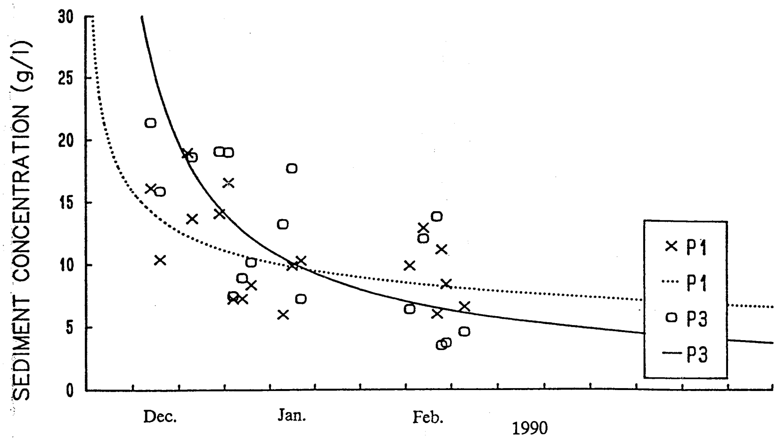

Fig. 3 Variations in the sediment concentration at P1 and P3 from December, 1989 to February, 1990.

(4) The sediment concentration at P1 decreases more slowly than at P3 in the late rainy season.

(5) The sediment concentration C (g/l) is related to time (day) counted since the first rain event in the rainy season by the following correlation curve:

$$C = 32.2T - 0.32 \quad r = -0.48 \text{ at P1} \tag{3}$$

$$C = 154.4T - 0.73 \quad r = -0.66 \text{ at P3} \tag{4}$$

where T is the number of days since the first rain event in the rainy season.

The above (3) term suggests that the decreasing of sediment concentration in the beginning of rainy season is controlled by the erodible soil amount on the ground, and the (4) suggests that the decreasing in the late rainy season is controlled by the developing vegetation. The authors consider that the dispersion of the correlation is caused by the variation of energy of rain drops that means rainfall intensity and the variation of antecedent soil moisture condition.

Figure 4 shows changes of the erodible soil amount, vegetation coverage and soil erosion amount at P1 and P4 from December, 1990 to February, 1991. The relationship of correlation between the sediment concentration and time in 1991 is shown by the following equation at P1.

$$C = 25.1T - 0.41 \quad r = -0.58 \text{ at P1 in 1991} \tag{5}$$

The relation is approximately similar to equation (3) for 1990. Figure 4 indicates that there is more erodible soil in the beginning of rainy season (1.2 mm) than in the late rainy season (0.8 mm). This decreasing tendency agrees with the results of soil erosion during the rainy season. These results suggest that the decreasing of sediment concentration in the beginning of rainy season is controlled by the existence amount of erodible soil.

Vegetation cover at the plot P4 covered with grasses is less than 20% up to January 7 in the beginning of rainy season, but it increases after the heavy rain of 70 mm on

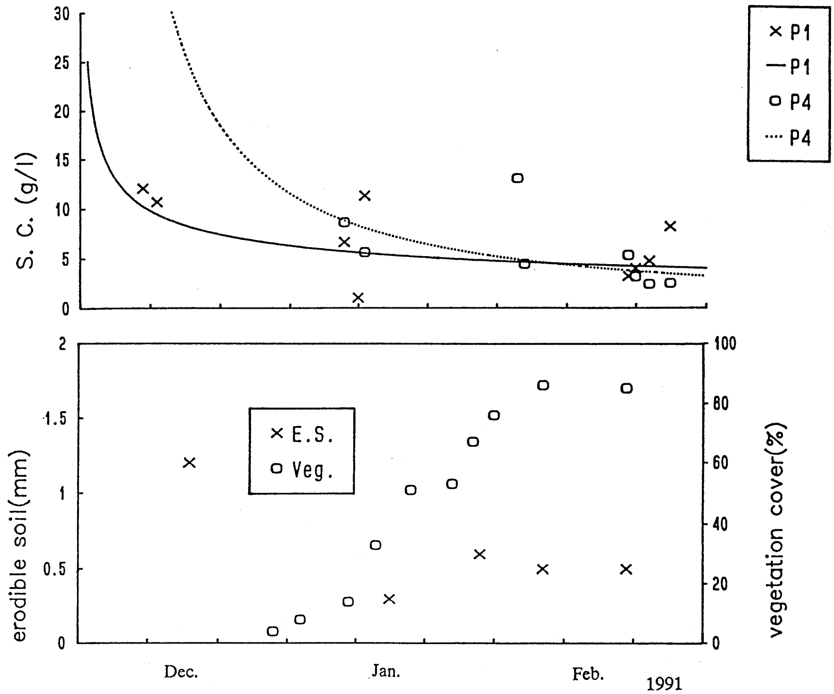

Fig. 4 Variations in the sediment concentration at P1 and P4, the erodible soil amount on the bare land, and the vegetation coverage at P4.

January 7, and it reaches 80% at the beginning of February in 1991. This gradually increasing tendency is similar to the reverse of the decreasing tendency of sediment yield at P4.

From the above results, the authors infer that the factors controlling sediment yield on the inter-rill area in the similar morphologic condition are the overland flow velocity and its amount, the amount of erodible soil yielded by weathering and deposited by wind on the slope especially during the dry season, and the growth and development of vegetation.

Forecasting of sediment yield

For forecasting of soil erosion rate on the gentle slope in a semi-arid zone, the present paper led the following equation of relationship among the soil erosion (S), runoff (Q) and time (T) since the first rain event of the rainy season:

$$S = 32.2QT - 0.32 \quad \text{at P1} \tag{6}$$

$$S = 197.3QT - 0.71 \quad \text{at P2} \tag{7}$$

$$S = 154.4QT - 0.73 \quad \text{at P3} \tag{8}$$

In the present research, the authors measured the sediment yield of the rainy season in

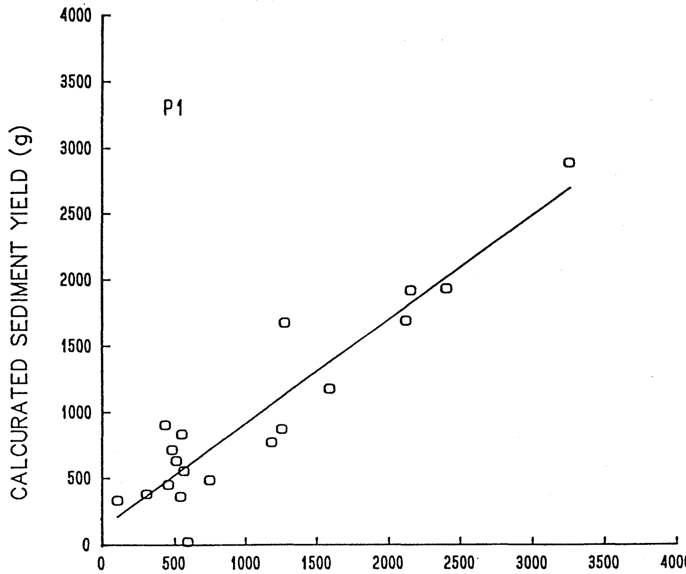

Fig. 5 Relationship between the measured sediment yield and calculated sediment yield.

1990 only from December, 1989 to February, 1990, though measured the runoff during the rainy season in 1990 (December, 1989 to April, 1990). For estimation of soil erosion rate in a whole year, the equations (6) to (8) and the measured runoff were used. Figure 5 shows the relationship between sediment yield calculated by equation (6) and the sediment yield measured at P1 from December, 1989 to February 1990. The calculated sediment yield amount approximately agrees with the measured one in this figure.

The soil erosion rate (mm/yr) is estimated from the following equation and the sediment yield amount (g/yr) that has been calculated by the above step.

$$SR = 10St/G/V/A \tag{9}$$

where SR is the annual soil erosion rate (mm/yr), St is the annual soil erosion amount (g), G is the specific gravity (g/cm^3), V is the volumetric solid content (%) and A is the area of plot (cm^2). From these parameters, the annual soil erosion rates were estimated as follows. Soil erosion rate at the complete bare land was 3.1 mm/yr, on the area covered with an acacia tree was 1.0 mm/yr and on the grassland was 1.2 mm/yr. These values are higher than the value of 0.7 mm/yr that Rapp *et al.* (1972) estimated from the sedimentation in the reservoir in the same region or the value on the steep slope in humid region (0.1 to 1.0 mm/yr) that Saunders & Young (1983) quoted in reviewing several studies. The above results supposed that the soil erosion may grow more seriously than in 1970 in this area, because of human activities such as the deforestation and grazing (Morishita, 1991). Especially, the extension of bare area caused by human activities makes the increasing of soil erosion accelerate, because the rainsplash, sheet erosion and "rain-flow transportation" act more effectively on the bare land than on the land covered with vegetation, and overland flow generate much on the bare area (Onodera, 1991).

The present paper can show quantitatively the seasonal variation. The value of 17% of the annual soil erosion rate yielded at P1 from December 5 to December 16, 1989, in the beginning of rainy season when 11% of the annual rainfall fell. While 50% of the annual soil erosion rate yielded from March to April, 1990 in the late rainy season when 55% of the annual rainfall fell.

CONCLUSIONS

The results of the present study are summarized as follows:

(1) The runoff and sediment yield indicate the clear relationship.

(2) Sediment concentration divided sediment yield by runoff decrease with time counted since the first rain event in the rainy season.

(3) In the beginning period of rainy season, the sediment concentration was very high, then rapidly decreased. This tendency is similar to the decreasing tendency of the erodible soil amount.

(4) In the late rainy season, the sediment concentration gradually decreased at P3. This tendency is similar to the reverse of the increasing tendency of vegetation coverage.

(5) The above results infer that the decreasing of the sediment concentration in the beginning of rainy season is controlled by the existence of the erodible soil amount on the ground, and the decreasing in late rainy season is controlled by the developing vegetation.

(6) The annual sediment yield were estimated from these results and clarified the relationships between sediment yield and its control factors. Soil erosion rate at the complete bare land was 3.1 mm/yr, on the land covered with an acacia tree was 1.0 mm/yr and on the grassland was 1.2 mm/yr.

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