Sediment-bound nutrient export from five small reservoir catchments and its implications for the Sudan savanna zone of Ghana

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Abstract

A study was carried out in the Sudan savanna zone in the Upper East Region of Ghana to assess the rate of sediment-bound nutrient export (NE) into five small reservoirs (Dua, Doba, Zebilla, Kumpalgogo and Bugri) and to analyse the implications of this export. The catchment soils and reservoir sediments from the various study sites were sampled and analysed for their bulk density, particle size distribution and nutrient content. Assessment of the nutrient concentrations indicated that the reservoir sediments were richer not only in nutrients and organic carbon, but also in clay and silt, than the catchment soils, having enrichment ratios >1. Nutrient export rates (NE; kg ha^{-1} $year^{-1}$) from the reservoir catchments ranged from 0.755 (±0.264) for OC, 0.104 (±0.0245) for N, 0.0020 (±0.0003) for P, 0.016 (±0.0038) for K, 0.009 (±0.0024) for Na, 0.113 (±0.017) for Ca and 0.027 (±0.0093) for Mg. These rates were lower than those of other studies, likely due to the low nutrient content in the catchment soils. The relationships established between NE and specific sediment yield (SSY) indicated the NE was positively correlated with SSY (R^2 = 0.66–0.98). The derived empirical equations can be satisfactorily used to predict the quantity of sediment-bound plant nutrients lost from similar catchments and subsequently stored in the reservoir sediments. The study results also suggest the need for sustainable land management practices to forestall erosion in the catchment areas and to reduce reservoir sedimentation, for enhancement of the livelihoods of the communities in the study area.

Key words

catchment soils, deposited sediment, Ghana, nutrient export, small reservoirs, soil erosion.

INTRODUCTION

Soil erosion is the most potent form of land degradation threatening sustainable agricultural production in Ghana (Folly 1997). The most severely affected areas are the three northern savanna regions, particularly the Upper East Region, where large tracts of land have been destroyed by water erosion through soil fertility decline, flooding and siltation of rivers and reservoirs (Quansah 2001).

The Upper East Region is characterized by a short, unimodal rainfall regime marked by severe fluctuations in time of onset, duration and intensity. Combined with poor water retention of the soils, these fluctuations cause large interannual variations in agricultural production. This leads, in turn, to insecure livelihoods for the region's inhabitants. Approximately 160 small reservoirs have been constructed over the years to deal with the interannual rainfall variations, by providing storage for significant quantities of water. These reservoirs provide water mainly for irrigation, particularly during the dry season, as well as for livestock and wildlife watering, fishing, domestic use, harbouring crocodiles and recreational purposes. Most of the reservoirs, however, may not last for half of their expected useful design lifetime because of the off-site siltation effects of erosion from their catchments (Adwubi *et al.* 2009). This was similar to findings

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of Tamene (2005) for the northern highlands of Ethiopia. Moreover, the eroded sediments are almost always accompanied by the export of sediment-bound nutrients and organic matter, which are deposited in the reservoirs. This can lead to eutrophication and degradation of the reservoir water quality (Krogvang 1990; Steegen *et al.* 2000; Withers & Lord 2002). More significantly, these nutrient losses can impact adversely on the productivity of the catchments, ultimately resulting in low biomass and crop yields, threatened food security and poverty (Stoorvogel & Smaling 1990; Bojö 1996; Eswaran *et al.* 2001; Verstraeten & Poesen 2002). These impacts are further exacerbated by the inability of the smallholder farmers in the affected areas to replenish the lost nutrients. Thus, meeting the future food needs and improved livelihoods of the communities in the Upper East Region would require goal-directed management of the soils for long-term productivity. To achieve the latter goal, the degradation of soil and waterbodies by erosion must be halted through restorative measures of sustainable soil, water, nutrient and crop management. Catchment area protection, using vegetative cover, would also be required to deal with erosion and the associated reservoir siltation problem. The design and implementation of erosion control measures, however, would require studies to establish the magnitude and extent of the erosion and productivity problem. This would facilitate the choice of appropriate sustainable land management technologies, providing the requisite baseline information for monitoring the effectiveness of the implemented technologies.

Numerous studies have been conducted in many parts of the world to assess nutrient export from catchments to their reservoirs. These include the studies of Johnson (1999) in Macoupin County, Illinois, Elias *et al.* (1998) for Kindo Koisha farms in southern Ethiopia, and Hengsdijk *et al.* (2005) for systems in Tigray, Ethiopia. Other than the studies of Akrasi and Ansa-Asare (2008) on nutrient transport to the Pra River basin, little research attention has been directed to sediment-bound nutrient export from catchments into small reservoirs in Ghana, especially in the Sudan savanna zone. Both published and unpublished data for Ghana to date reveal that most erosion studies have been directed at measuring soil loss and run-off rates in run-off plots (Bonsu & Obeng 1979; Quansah *et al.* 2000; Adama 2003).

The assessment of erosion and its off-site effects and impacts on nutrient and organic matter losses, as they influence the productivity of reservoir catchments, has never been studied, nor has the link between nutrient and organic matter losses from the erosion source area and nutrients in reservoir sediments in the Upper East Region of Ghana.

Thus, this study was carried out with the goal of contributing to the generation of the requisite data and information to fill this information gap. The specific objectives of this study are to: (i) Assess the variability in the nutrient contents of soil in the different catchments (erosion source) and the deposited sediment in their reservoirs, (ii) assess and evaluate the rate of nutrient export and (iii) establish a sediment yield/nutrient export relationship for predicting the annual rate of nutrient loss in similar agro-ecological locations.

MATERIALS AND METHODS

Study site

The study involved five representative small reservoirs in the Upper East Region of Ghana. Their characteristics are summarized in Table 1. The Upper East Region is the north-easternmost part of Ghana's 10 regions. It is located between latitudes 10°15′ and 11°10′ north, and longitudes 0° and 1° west. It covers an area of 8842 km^2 (IFAD 1991), comprising eight administrative districts (Bolga, Bongo, Builsa, Kasena-Nankana, Talensi Nabdam, Bawku West, Bawku East and Garu Tempani; Fig. 1). The region has a population of 920 089, comprising

Table 1. Characteristics of five study reservoirs in Upper East Region of Ghana

Reservoir	YR	A	SC	LS	DS	HD	SE	CE
Doba	1998	70	185	180.0	5	4.6	177	178
Dua	1997	35	99.6	98.6	1	4.2	228	229
Zebilla	1998	105	460.0	452.0	8	7	225.8	227.25
Kumpalgogo	1998	40	120.0	N/A	N/A	3.8	193	193
Bugri	1994	216	510.0	508.9	1.1	7.5	499.25	500.75

YR, year of rehabilitation; A, catchment area (ha); SC, design storage capacity (10^3 m^3); LS, live storage (10^3 m^3); DS, dead storage (10^3 m^3); HD, height of dam wall (m); SE, spillway elevation (m.s.l.); CE, dam crest elevation (m.s.l.).

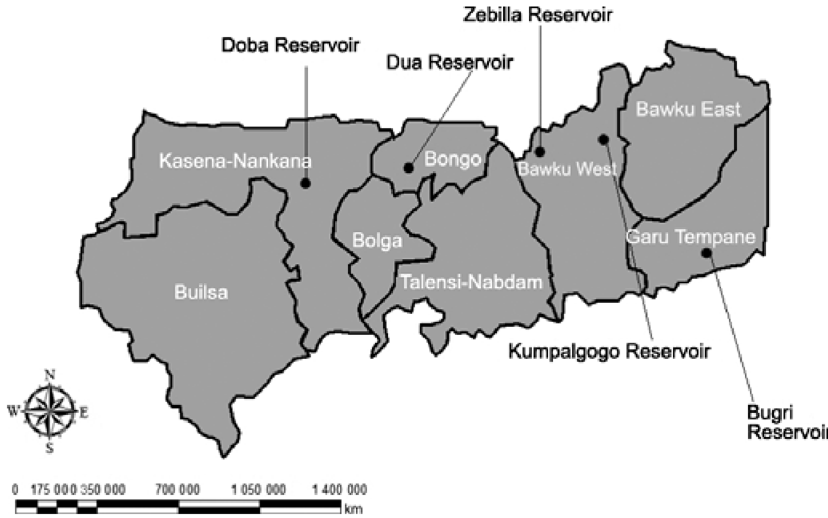

Fig. 1. Location of five study reservoirs and administrative districts in Upper East Region, Ghana.

442 492 men and 477 597 women. The population growth rate is 3% per annum (GSS, 2005). The region has a comparatively high population density of 104.1 persons km^{-2}, compared to a national average of 79.3 persons km^{-2}. Over 80% of the population live in the rural areas, with agriculture being their major economic activity (Birner *et al.* 2005).

The climate is semi-arid, with a unimodal precipitation pattern of about 1000 mm $year^{-1}$, lasting from 5 to 6 months and followed by 6 to 7 months of dry period. Precipitation is often erratic, with considerable variations existing between successive rainy seasons in regard to the time of onset, duration and quantity of precipitation. Precipitation intensities are high, often exceeding soil infiltrability, with a consequent generation of large volumes of run-off having a high potential to cause erosion (Liebe *et al.* 2005). Temperatures are consistently high, with an average of 28.6°C. The average annual relative humidity is 55%. Thus, there is a high variability in temperature and relative humidity, resulting in high evapotranspiration levels that average 1652 mm $year^{-1}$. The aridity index is 0.54. The vegetation is Sudan savanna, consisting of short drought- and fire-resistant deciduous trees, interspersed with open savanna grasslands. Grass is very sparse, with most areas exhibiting severely eroded soils, which comprise Luvisols, Cambisols, Gleysols, Regosols, Vertisols, Plinthosols and Fluvisols developed from granites, Birimian rocks and alluvia of mixed origin (Asiamah 1992). A large part of the area (82%) is underlain by metamorphic and igneous complexes, with gneiss and granodiorite predominating. Where hills rise above the soil surface, they consist of greenstone and schist (Fig. 2). A substantial band of sandstone, grit and conglomerate parallels the boundary, and the course of the White Volta in the south-eastern boundary area of the region. There are small areas of intrusive diorite in the northwest of the region. Petroplinthite has been formed by fluvial processes over large areas of flat lands adjacent to present and past water courses. Sand occurs as local deposits and along most of the major river courses.

Sampling site selection

Owing to time and limited financial resources, it was not possible to carry out this study on all the reservoirs in the region. Rather, it was necessary to select sites representative of the catchments in the region. Accordingly, five representative reservoirs were selected for the study (Fig. 1). This selection was made on the basis of a desk study and a reconnaissance survey based on the following criteria:

- Dugouts and desilted reservoirs were omitted;
- The size of reservoir was considered, in terms of small, medium and large;
- Reservoirs with available design maps and rehabilitated (raising of dam wall, etc) between 1990 and 1998 were considered; and
- The spatial distribution of catchments to cover the entire region

A large proportion of the study catchments had gentle slopes (<5%). In the upslope reaches of the catchment, however, where homesteads and compound farms were located, the slopes could reach 10%. All the reservoirs had patches of marshy land of varying sizes surrounding them. These marshy sites served as sinks for sediment transported from the source areas, thereby reducing the quantity of sediment reaching the reservoirs. Some of the marshy sites were planted with rice. Land use in the catchments comprised compound farms cultivated for a variety of crops, including millet, sorghum and okra. The cultivation practices, including bullock plowing, tended to

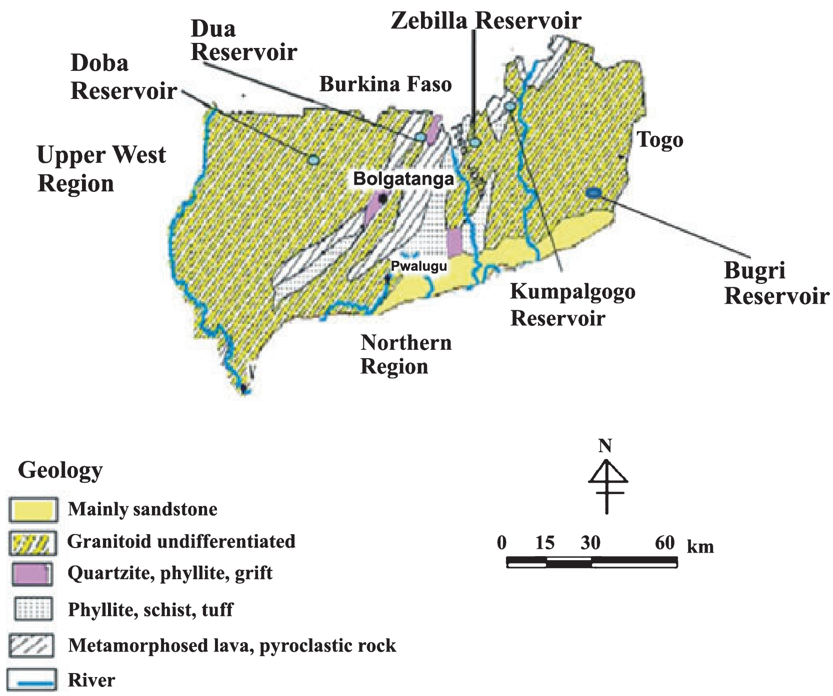

Fig. 2. Geology map of Upper East Region, Ghana, showing study sites (Kesse 1985).

loosen the soil, making them more erodible. In some cases, vegetables were cultivated very close to the periphery of the reservoirs, as observed at Zebilla. Nutrient management mainly involved the use of farmyard manure and compost, which are often inadequate. Mineral fertilizers are scarcely used. Thus, crop production in the catchments depended mainly on the inherent low natural fertility of the soils. Some of the reservoirs (Doba, Dua, Bugri and Kumpalgogo) had lines or patches of vetiver along the periphery, the dam wall and the reservoir spillways.

Focus group discussion

Focus group discussions were organized for farmers in all the study areas. A checklist was used to collect the necessary data and information on catchment and reservoir management. The information on catchment management included the type of crops cultivated, pattern of cultivation, fertilizer use, catchment area protection, soil management practices. Reservoir management information included the alternative uses of the water in the reservoir, especially in the dry season.

Soil sampling and analysis of their nutrient contents

Catchment soils

Soil samples were taken in each catchment to a depth of 0–15 cm from the upper, middle and lower toposites, as the soil variability followed the soil catena. A composite sample, made up of 10 bulked representative samples, was taken at each toposite for soil physical and chemical analyses.

Reservoir sediments

Undisturbed wet sediment samples of known volume were taken from each reservoir with a Beeker Sampler. The Beeker sampler is a piston corer with clear perspex tubes (Ø = 57 mm) of different lengths (600, 1000 and 1500 mm). An inflatable valve at the bottom of the piston assures no sediment losses when raising the piston corer to the surface. Both disturbed and undisturbed soil samples were taken from each reservoir at each of the following locations: (i) 10 m away from the upstream end of the reservoir, (ii) 5–10 m away from the dam wall, (iii) in the middle of the reservoir and (iv) the remaining samples were taken from other locations in the reservoir. A total of ten samples were collected from each reservoir, with two samples per sampling site. One sample per sampling site was used to determine sediment bulk density, and the other for the sediment particle size and determination of soil chemical properties.

Soil chemical and physical analysis

The following chemical parameters were determined: pH by a Suntex pH (mv) Sp meter (701) for a soil:water ratio of 1:2.5 (McLean 1982), OC with a modified Walkley-Black wet oxidation method (Nelson & Sommers 1982), total nitrogen (N) by Kjeldahl digestion and distillation procedure (Bremner & Mulvaney 1982), available phosphorus (P) with the Bray P_1 method (Olsen & Sommers 1982); exchangeable bases (calcium, magnesium, potassium and sodium) were determined in 1.0 mol L^{-1} ammonium acetate (NH_4OAc) extract (Black 1965) and the exchangeable acidity hydrogen and aluminium in 1.0 mol L^{-1} sodium chloride (KCl) extract (McLean 1965). Particle size distribution was determined with the hydrometer method (Bouyoucos 1963), and the bulk density of the catchment soils was determined with the metal core sampler method (Blake & Harte 1986).

Calculation of nutrient enrichment ratios (ER)

Nutrients are strongly adsorbed to the finer soil fractions, which are preferentially transported by the sedimentation processes because the finer soil fractions have high specific surface areas (Haregeweyn *et al.* 2008). Thus, eroded sediments are richer in nutrients and colloidal clay than the soil from which they originated. The enrichment ratio (ER) is a measure of the magnitude of richness. The enrichment ratio was determined as follows (Wan & El-Swaify 1998):

$$\mathrm{ER} = \frac{\text{Concentration of a constituent such as OC, N and others in the eroded sediment}}{\text{Concentration of the same constituent in the } \textit{in situ} \text{ soil}}. \quad (1)$$

the current water storage capacity from the initial water storage capacity. The sediment trap efficiency (STE) is the proportion of the incoming sediment that is deposited or trapped in a reservoir (Heinemann, 1981). The weight of deposited sediment was adjusted for the reservoir STE to determine the average sediment yield from the contributing watersheds. The calculation proposed by Brown (1943) was used to estimate the STE of the reservoirs. Adwubi *et al.* (2009) provide the details of the reservoir sediment studies. The measured sediment yield data (Table 2) were used in the analysis of NE. The nutrient trap efficiency in this study was considered to be equal to the STE. The reasons for this assumption are that the reservoirs have a high run-off trap efficiency, as no spillage has occurred (i.e., STE = 99%; see Table 2) since constructions of most of the reservoirs because of insufficient run-off inflow, and because the stored water is being used for irrigation during the dry period, once the sediment has settled in the reservoirs. Such assumptions may not be applicable for small flood retention ponds, however, because their retention capacity is limited (Haregeweyn *et al.* 2008).

Quantification and evaluation of nutrient export rates

The sediment-bound nutrient export (NE) value for each catchment draining to the respective reservoirs was calculated as follows (modified after Verstraeten & Poesen 2002):

$$\mathrm{NE} = \frac{\mathrm{SM} \times \mathrm{NC}}{A \times Y \times \mathrm{NTE} \times 10}, \quad (2)$$

$$\mathrm{SM} = \mathrm{SV} \times \rho_b, \quad (3)$$

where NE = nutrient export (kg ha^{-1} $year^{-1}$), SM = total measured sediment mass (kg), NC = average nutrient content of sample (mg nutrient kg $sediment^{-1}$), A = catchment area (ha), Y = age of reservoir for the duration of sediment accumulation; NTE (= STE) = nutrient (= sediment) trap efficiency of the reservoirs (%), SV = total measured sediment volume (m^3) in the reservoir and ρ_b = dry bulk density (kg m^{-3}).

Sediment deposition in all the studied reservoirs was quantified using bathymetric survey. The total volume of sediment deposition was then calculated by subtracting

Statistical analysis

The data obtained were analysed by analysis of variance (ANOVA), using the GENSTAT Statistical Package (GENSTAT, 2007) to determine the variability in bulk density and sediment nutrients. Standard error difference (s.e.d.) at 5% was used to compare the treatment means. Mean

Table 2. Trap efficiency, sediment mass, sediment yield and area-specific sediment yield of five study reservoirs in the Upper East Region of Ghana

Reservoirs	STE (%)	SM (t)	SY (t $year^{-1}$)	SSY (t ha^{-1} $year^{-1}$)
Dua	97.86	35 183	3595.24	102.72
Doba	98.16	11 480	1299.47	18.56
Zebilla	98.86	24 849	2792.84	26.60
Kumpalgogo	97.70	55 413	6301.94	157.55
Bugri	98.03	50 310	3947.77	18.28
Average	98.12	35447	3587.45	64.74

SM, sediment deposit; SY, sediment yield; SSY, specific sediment yield; TE, sediment trap efficiency; SM, sediment mass; NTE, nutrient trap efficiency.

comparison, bivariate correlation matrixes were used to assess the degree of association between the catchment soils and sediment deposits. Regression analysis was used to generate empirical equations to predict the quantity of soil nutrients lost from reservoir catchments and deposited in the reservoir sediments. The nutrient status of the catchment soils and deposited sediments was evaluated on the basis of the Soil Interpretation Guide of Landon (1991).

RESULTS AND DISCUSSION

Physical characteristics of the reservoir sediments and catchment soils

Bulk density

The results of the bulk density analysis, and the texture of the catchment soils and reservoir sediments, are summarized in Table 3. The mean dry bulk densities of the catchment soils were 1.52, 1.63, 1.72, 1.6 and 1.49 for Dua, Doba, Zebilla, Kumpalgogo and Bugri, respectively (Table 3). The mean, standard error difference (s.e.d.) and CV were 1.59 t m^{-3}, 0.08 and 6.2%, respectively. Considering a bulk density range of 1.1–1.4 t m^{-3} for surface mineral soils that were not recently cultivated, but also not compacted (Landon 1991), these values are relatively high and may present restrictions to root growth and reduced air-filled porosity, with increasing adverse effects in the case of the 1.6–1.72 t m^{-3} for the Doba, Zebilla and Bugri catchments, in which the crop cultivation was more intense. Soil compaction as a result of trampling by cattle, sheep and goats, a common feature of free range grazing and raindrop impact in the sparsely vegetated catchments, could contribute to the increased sediment bulk density.

However, the mean dry bulk densities of the sediment deposits ranged between 0.96 and 1.53 t m^{-3} (Table 3). Doba and Dua reservoirs exhibited significantly higher bulk densities than Zebilla and Bugri reservoirs. These values are comparable to the range of 0.78–1.35 t m^{-3} reported for reservoir sediments by Verstraeten and Poesen (2001). The difference in bulk density between Doba and Zebilla was also significant. The bulk density values are indicative of the degree of compaction of the deposited sediments. Sediment bulk density increases with increasing compaction. There was a considerable variation (CV = 41.9%) in the measured bulk densities between the studied reservoirs, which falls within the medium variation class based on Warrick's (1998) guidelines for variability of soil properties. The variations, as observed in a similar study by Verstraeten and Poesen (2001), may be the result of different hydrologic conditions of the reservoirs, and differences in sediment texture between the reservoir deposits and their interactions. Sands and sandy loams in topsoils tend to have higher bulk densities than clay and clay loams (Landon 1991). The results of this study indicated the bulk density of the sandy loam reservoir sediments of Doba to be 12–13% higher than the clay loam sediments of Dua, Zebilla and Kumpalgogo, and 24% higher than the clay of the Bugri sediments. The nature and quantity of organic matter content also influences dry bulk density. Deposits with high quantities of litter have unusually low dry bulk density values. Within-reservoir variability also was observed in the bulk density samples. The variability, as observed in a similar study by Verstraeten and Poesen (2001), may be because of spatially distributed patterns of bulk density within the reservoir which, in turn, are controlled by the flow distance from the reservoir

Table 3. Bulk densities and particle sizes of five study catchment soils and their reservoir sediments in the Upper East Region of Ghana

	Catchment soil					Reservoir Sediment				
Site	ρ_b (t m^{-3})	Sand	Clay (%)	Silt	Texture	ρ_b (t m^{-3})	Sand	Clay (%)	Silt	Texture
Dua	1.52	88	4.13	7.87	Sand	1.35	28	33.9	38.1	Clay loam
Doba	1.63	87.73	4.27	8	Sand	1.53	70.7	16.5	12.8	Sandy loam
Zebilla	1.72	90.4	2.53	7.07	Sand	0.96	30.7	31.9	37.5	Clay loam
Kumpalgogo	1.6	83.87	9.07	7.07	Loamy sand	1.33	28.7	39.2	32.1	Clay loam
Bugri	1.49	81.07	9.2	9.73	Loamy sand	1.17	22.7	48.5	28.8	Clay
Average	1.592	86.214	5.84	7.948		1.268	36.16	34	29.86	
s.e.d.	0.0807	1.985	1.898	1.7		0.43	7.41	5.49	6.19	
CV(%)	6.2	2.8	39.8	26.2		41.9	25.1	19.8	25.4	

ρ_b, dry bulk density (t m^{-3}); s.e.d., standard error difference; CV, coefficient of variation.

inlet to the reservoir outlet and by spatially hydrologic conditions within the reservoir.

A comparison of the sediment bulk density of the reservoirs and the catchments indicated less variability in the latter. The mean values indicated the reservoir sediments were loose and more porous than the catchment soils.

Particle sizes

The mean particle sizes of the reservoir catchment soils and sediment deposits are summarized in Table 3. The values for the catchments ranged from 81.07% to 90.4%, 2.53% to 9.2% and 7.07% to 9.73% for sand, clay and silt, respectively. The catchment soils had more sand than clay and silt. However, the mean particle sizes of the sediment deposits ranged from 22.7% to 70.7%, 16.5% to 48.5% and 12.8% to 38.1% for sand, clay and silt, respectively (Table 3). Thus, the reservoir sediment deposits were richer in clay and silt than the catchment soils. This confirms the selectivity of the sediment transport process in removing finer particles rich in nutrients from the erosion source. The differences in the sediment texture of the various reservoirs reflect the variability in soil type, magnitude of fine particle selectivity by erosion process, topography, rainfall-run-off characteristics, crop cover and organic matter content of the soils in the study reservoir catchments.

Nutrient concentrations in the catchment soils and reservoir sediments

Soil erosion and sediment delivery processes are not only responsible for high sediment transport rates, but also for the associated export of sediment-bound nutrients that are finally deposited in the reservoir. The spatial variability in the pH and soil nutrient content in the various catchments (erosion source), and the deposited sediments in their respective reservoirs in this study were assessed, with the results summarized in Tables 4–8.

pH

The pH of the catchment soils ranged between 5.23 and 6.43 for the Kumpalgogo and Bugri catchments, respectively (Table 4). According to Landon (1991), the pH values indicate strongly acidic soils in the Kumpalgogo and Zebilla catchments, moderately acidic soils in the Doba and Dua catchments, and slightly acid soil for the Bugri catchment. The sediments of Kumpalgogo and Bugri reservoirs were very strongly acidic, strongly acidic for Doba and Zebilla, and moderately acidic for Dua. As the sediments in the reservoirs were produced in these catchments, it is not surprising their pH is in the acidic range, with values varying from 4.85 to 6.07 (Table 5). The low organic matter content of the soils, and the acidic granitic parent material of most of the soils, may account for the observed low soil pH. A comparison of the pH of the catchment sediments and of their respective reservoirs showed the values to be positively, but not significantly, correlated (Table 6). As observed by Haregeweyn *et al.* (2008) in a similar study, this poor correlation could be attributable to the variability in such parameters as moisture content and basic cation concentrations.

Organic carbon (OC)

The per cent organic carbon of the catchments (Table 4) ranged between 0.48 and 1.0. The differences in the OC

Table 4. Soil nutrient concentration in five study catchments in the Upper East Region of Ghana

	pH	OC	N	P	K	Na	Ca	Mg	Al	H				
Catchments	(1:2.5)	(%)					mg kg				C:N	Ca:Mg	K:Mg	ECEC
Dua	5.76	0.547	0.0722	20.2	231	135	969	130.7	80	24.4	0.94	7.38	1.79	1569
Doba	5.53	0.998	0.08	16	406	91	796	109.3	60	29.8	12.41	7.29	3.76	1492
Zebilla	5.31	0.909	0.0567	23.8	39	59	702	133.3	72	31.1	16.04	5.45	0.29	1037
Kumpalgogo	5.23	0.479	0.1033	15.7	639	201	836	157.3	64	31.1	4.62	5.27	4.07	1928
Bugri	6.43	0.814	0.0889	21.6	1434	200	1142	138.7	60	28.4	9.72	8.5	9.66	3003
Average	5.65	0.75	0.080	19.46	549.8	137.2	889	133.86	67.2	28.96	8.75	6.78	3.91	1805.8
s.e.d.	0.329	0.1656	0.0154	3.88	514.1	53.9	261	21.52	10.18	6.55	1.986	1.651	2.725	500.9
CV (%)	7.1	27.1	23.5	24.4	114.5	48.2	36	19.7	18.6	27.7	27.8	29.8	85.3	34

pH, hydrogen ion concentration; OC, organic carbon; N, total nitrogen; P, available phosphorus; K, potassium; Na, sodium; Ca, calcium; Mg, magnesium; Al, aluminium; H, hydrogen; C:N, carbon nitrogen ratio; Ca:Mg, calcium magnesium ratio; K:Mg, potassium magnesium ratio; ECEC, effective cation exchange capacity; s.e.d., standard error difference; CV, coefficient of variation.

Table 5. Nutrient concentration of sediment deposits in five study reservoirs in the Upper East Region of Ghana

	pH	OC	N	P	K	Na	Ca	Mg	Al	H				
Reservoirs	(1:2.5)	(%)					mg kg				C:N	Ca:Mg	K:Mg	ECEC
Dua	6.07	0.593	0.053	35	289	183	2147	480	66	17.3	11.31	4.8	0.657	3182
Doba	5.37	1.453	0.093	24.3	354	107	1573	688	78	32	16.73	2.41	0.527	2832
Zebilla	5.53	1.393	0.26	29.4	251	131	4173	776	66	16	6.65	5.37	0.324	5413
Kumpalgogo	4.85	1.42	0.22	30.7	199	103	1093	312	126	22.7	6.37	3.88	0.703	1856
Bugri	5.24	1.577	0.163	13.5	177	117	1853	272	132	14.7	9.7	7.81	0.824	2566
Average	5.41	1.29	0.16	26.58	254	128.2	2167.8	505.6	93.6	20.54	10.15	4.85	0.61	3169.8
s.e.d.	0.498	0.2426	0.0475	4.78	59.6	34.5	327.5	123.9	24.07	5.78	2.664	1.491	0.2712	446.2
CV (%)	11.3	23.1	36.8	22	28.8	32.9	18.5	30	31.5	34.5	32.1	37.6	54.7	17.2

pH, hydrogen ion concentration; OC, organic carbon; N, total nitrogen; P, available phosphorus; K, potassium; Na, sodium; Ca, calcium; Mg, magnesium; Al, aluminium; H, hydrogen; C:N, carbon nitrogen ratio; Ca:Mg, calcium magnesium ratio; K:Mg, potassium magnesium ratio; ECEC, effective cation exchange capacity; s.e.d., standard error difference; CV, coefficient of variation.

Table 6. Paired mean comparison and sample correlations of catchment and reservoir soils

	Mean comparison		Correlation	
Pairs	Paired mean difference	d.f.	*R*	*n*
pH_C and pH_R	0.24	4	0.16	5
OC_C and OC_R	−0.54*	4	0.51	5
N_C and N_R	−0.08	4	−0.01	5
P_C and P_R	−7.12	4	−0.15	5
K_C and K_R	295.80	4	−0.63	5
Na_C and Na_R	9.00	4	−0.20	5
Ca_C and Ca_R	0.0013	4	−0.42	5
Mg_C and Mg_R	−0.037*	4	−0.66	5
Al_C and Al_R	−26.40	4	−0.66	5
H_C and H_R	−8.42*	4	−0.29	5

*Significant at 0.05 level, underscores 'C'and 'R' stand for catchment and reservoir, respectively. *R*, correlation coefficient; d.f., degrees of freedom; *n*, number of samples.

content were significant, except for that between Doba and Zebilla, and Zebilla and Bugri. According to Warrick (1998), the percent variation between the maximum and minimum OC content (0.52), and the coefficient of variation (CV) observed in this study, falls within medium variability. The variations in the organic carbon content of the catchment soils may be due, among several factors, to the soil type, the quantity of organic amendments applied by farmers in the catchments and the quantity of cattle manure from free range livestock grazing. Focus group discussions with farmers in Doba, for example, revealed that most of them use organic manure as nutrient amendment, rather than mineral fertilizer, which may account for the high OC content of their catchment soils, compared to the others.

The organic carbon in the reservoirs varied from 0.59% to 1.58%, with a mean value of 1.29% (Table 5). The differences in OC content between Bugri, Doba, Kumpalgogo and Zebilla were not significant, although they all exhibited a higher OC than Dua. The variation between the maximum and minimum OC content of the reservoir sediments was 0.98%. The variability in OC content, indicated by a CV value of 23.1%, was medium.

A comparison of the catchment and reservoir organic carbon content (Tables 4 and 5) indicated the reservoir sediments were richer in organic carbon. The concentration of organic matter, which is the source of carbon in the surface soil of the catchments, its low density and one of the first soil constituents to be removed through erosion and transported downslope are implicated by the higher concentrations of organic carbon in the sediments deposited in the reservoirs. Furthermore, the submergence of the reservoir sediments for most part of the year in water (i.e., under anoxic conditions) could facilitate a slower rate of organic matter decomposition than that of the well-drained catchment soils. Thus, a higher level of organic carbon is maintained in the poorly drained reservoir sediments. The results of the paired mean comparisons (Table 6) indicated the differences in the OC content of the catchment soils, and the reservoir sediments to be highly significant ($P < 0.05$). The OC content of the catchment soils was positively correlated with that of the reservoir sediments (Table 6), although the correlation coefficient was not significant. The implication is that the catchments were not the only source of the organic carbon in the reservoir sediments. Other possible sources of organic carbon in the sediments are biodeposits from livestock.

Total nitrogen (N)

The mean total nitrogen ranged between 0.06% and 0.10% with a mean value of 0.08% in the catchment soils (Table 4). The differences in total nitrogen (TN) between the catchments were significant. The farmers use more mineral fertilizers (in the form of NPK, sulphate of ammonia and urea) in the Kumpalgogo and Bugri catchments, which account for the high TN content of the soils. In the Kumpalgogo and Bugri catchments, for example, farmers apply four bags of these mineral fertilizers per acre of land, compared to two bags per acre applied in the other reservoir catchments. The mean TN in the reservoir sediments, however, varied from 0.05% to 0.26%, with a mean value of 0.16% (Table 5). The total nitrogen in the Zebilla reservoir sediments was significantly higher than that of all the other reservoirs. While there were no significant differences in the total nitrogen in the Zebilla and Kumpalgogo reservoirs, the two reservoirs recorded significantly higher total nitrogen than the Dua, Doba and Bugri reservoirs, which had similar total nitrogen contents.

A comparison of the TN of the reservoir sediments to those of the catchment soils indicated the former to be richer in TN and more varied (CV = 36.8%) than the catchment soils (CV = 23.5%). Urine from cattle, sheep, goats and birds that visit the reservoirs to drink water is a contributing factor to the higher nitrogen levels in the reservoir sediments. The paired mean comparisons (Table 6) indicated the differences in total nitrogen to be significant. There was also a negative, but not significant, correlation ($r = -0.01$) between the nitrogen in the catchment soils and those in the reservoir sediments. The results also indicated that the total nitrogen in the sediments deposited in the reservoirs was of organic origin, as it is strongly correlated with organic carbon ($r = 0.61$; Table 7). A similar observation was made by Ortt *et al.* (2000), with the correlation coefficient (r) being 0.84.

Available phosphorus (P)

Available phosphorus (P) ranged from 15.7 to 23.8 mg kg^{-1} for Kumpalgogo and Zebilla catchments, respectively, with a mean value of 19.46 mg kg^{-1} in the catchment soils (Table 4). The differences in Zebilla, Bugri and Dua were significantly higher than for Doba and Kumpalgogo. For the reservoir sediments, the P ranged from 13.5 to 35.0 mg kg^{-1}, with a mean value of 26.58 mg kg^{-1} (Table 5). The differences for Dua, Kumpalgogo and Zebilla, which were not significant, were significantly greater than those for Bugri and Doba. The P level for the reservoirs was significantly higher than for the catchments (Tables 4 and 5). This may be partly explained by the strong positive correlation between available P and silt ($r = 0.70$; Table 7), which is the most erodible soil textural fraction from the catchments. A large population of donkeys were observed in the Dua catchment, as well as an abattoir and a heap of

Table 7. Pearson's correlations matrix for sediment nutrients and textural classes for the five study reservoirs in the Upper East Region of Ghana

	OC	N	P	K	Na	Ca	Mg	Al	H	Sand	Clay	Silt
pH	−0.82*	−0.59	0.40	0.50	0.92*	0.43	0.39	−0.78	−0.27	0.04	−0.50	0.57
OC		0.61	0.71	−0.34	−0.93*	−0.06	−0.05	0.56	0.20	0.07	0.48	−0.67
N			−0.09	−0.59	−0.51	0.44	0.07	0.29	−0.31	−0.20	0.04	0.17
P				0.36	0.52	0.17	0.33	−0.60	0.08	0.29	−0.83*	0.70
K					0.22	0.05	0.71	−0.77	0.68	0.87*	−0.67	−0.12
Na						0.31	0.10	−0.59	−0.46	−0.23	−0.40	0.74
Ca							0.68	−0.60	−0.49	−0.001	−0.49	0.61
Mg								−0.85*	0.30	0.73	−0.80	0.19
Al									−0.13	−0.56	0.89*	−0.49
H										0.87*	−0.25	−0.63
Sand											−0.63	−0.31
Clay												−0.54

*Correlation significant at 0.05 level.

donkey dung mixed with urine, was found close to the Dua reservoir. In the rainy season, part of the heap is washed into the reservoir, contributing to the sediment P content.

The reservoir P, however, was negatively correlated with the clay, but positively with the sand fractions. The implication is that available P decreases as the clay fraction of the soil increases, and the sand fraction decreases. In the former case, the clay fraction fixes the phosphate ions (Ongley 1982; Sibbesen 1995; Haregeweyn *et al.* 2008), while the P is leached in the latter case. There also is a negative correlation between the reservoir P and Al. Increased Al, which leads to increased acidity, decreases the quantity of available P. At low pH values (<5.5), phosphate ions combine with iron and aluminium to form compounds that are not readily available to plants (Landon 1991).

Although the contributions was not quantified in this study, the other possible reason for the high P level in the reservoirs is the addition of manure from cattle, sheep, goats and birds that visit the reservoirs to drink water. Crop residues transported by run-off and deposited in the reservoirs constitute another P source. Nevertheless, the contribution of these P sources merits further quantitative study.

Exchangeable potassium (K)

The potassium (K) content of the catchment soils varied from 39 to 1434 mg kg^{-1}, with a mean value of 549.8 mg kg^{-1} (Table 4). Bugri exhibited a significantly higher K content than all the other catchments. In spite of the wide variation in the magnitude of K content in the catchment soils (CV = 114.5%), the differences for Kumpalgogo, Zebilla, Doba and Dua were not significant. The reservoir sediments exhibited a higher concentration of K than those of the Dua and Zebilla catchment soils. The K concentrations in the other reservoirs were lower than that in their catchments. The paired mean differences between the catchment and the reservoir sediments, however, were not significant. The K content of the sediments ranged between 177 and 354 mg kg^{-1}, with a mean value of 254 mg kg^{-1} (Table 5). The K content of Doba reservoir was significantly greater than all the other reservoirs. Significant differences also were observed between Dua and Bugri and Kumpalgogo, and Zebilla and Bugri. All other differences were not significant. The catchment K was correlated negatively ($r = -0.63$; Table 6) with the reservoir K. Although the correlation was not significant, it suggests sources other than the catchment for the K in the reservoir sediments. However, the negative correlation between the K and clay and organic carbon contents of the reservoir sediments (Table 7) could imply most of the reservoir K was in solution.

Exchangeable sodium (Na)

The mean exchangeable sodium (Na) content of the catchment soils (Table 4) ranged from 59 to 201 mg kg^{-1}, with a mean value of 137.2 mg kg^{-1}. The Bugri and Kumpalgogo catchments exhibited significantly higher Na content than all the remaining catchments. The difference in the Na content of Dua and Zebilla also was significant.

The magnitude of the Na content of the catchments and reservoirs varied. The Dua, Doba and Zebilla reservoirs exhibited higher K concentrations, while Kumpalgogo and Bugri had lower concentrations than their contributing catchments. The paired mean differences, however, were not significant (Table 6). The Na concentration in the reservoir sediments correlated poorly and negatively with that of the catchments ($r = -0.20$; Table 6). As with K, this finding could imply other sources for the sediment Na, such as the urine of cattle that drink water from the reservoirs. Most of the reservoir Na also may be in solution.

Exchangeable calcium (Ca)

The concentration of calcium in the catchment soils ranged from 702 to 1142 mg kg^{-1}, with a mean value of 889 mg kg^{-1} (Table 4). The difference in calcium concentration of the Dua, Doba and Kumpalgogo, as well as that of Dua and Bugri, was not significant. All other differences were significant. The variation (CV = 36%) was rated as medium (Warrick 1998). The exchangeable calcium in the reservoir sediments varied from 1093 to 4173 mg kg^{-1}, with a mean value of 2167.8 mg kg^{-1} (Table 5). The differences in the reservoir Ca were significant. The variation (CV = 18.5%) in the Ca concentration in the various reservoirs was rated medium. The reservoir sediments exhibited significantly higher Ca concentrations, however, than those of the catchment soils (Tables 4 and 5).

Although the paired mean differences in Ca between the catchment and reservoirs were not significant, the exchangeable Ca of the catchment soils correlated negatively with that in the reservoir sediments (Table 6), implying other Ca sources in the reservoirs. The implication of the poor correlation between the Ca and clay concentrations of the reservoir sediments (Table 7) is that run-off is the main calcium transportation agent from the catchments to the reservoirs, similar to findings reported in a study by Haregeweyn *et al.* (2008).

Exchangeable magnesium (Mg)

The exchangeable Mg concentration of the catchment soils varied between 109.3 and 157.3 mg kg^{-1}, with a mean value of 133.9 mg kg^{-1} (Table 4). The Doba and Kumpalgogo catchments exhibited the lowest and highest Mg concentrations, respectively, with the differences being significant. For the reservoir sediments, the magnesium concentrations ranged from 272 to 776 mg kg^{-1}, with a mean value of 505.6 mg kg^{-1} (Table 5). Significant differences in the reservoir Ca concentrations was observed, with the variation (CV = 30%) being medium. The reservoir sediments exhibited significantly higher Mg concentration than the catchment soils, and the two were not significantly correlated ($r = -0.66$; Table 6) as was observed for calcium.

Aluminium (Al)

The mean Al concentration in the catchment soils (Table 4) ranged from 60 to 80 mg kg^{-1}, with a mean value of 67.2 mg kg^{-1}. The Dua and Zebilla exhibited significantly higher concentrations than the Doba and Bugri catchments. The latter two catchments and Kumpalgogo did not differ significantly in their Al concentrations.

The reservoir sediments exhibited a range of 66 to 132 mg kg^{-1} Al, with a mean value of 20.54 mg kg^{-1} (Table 5). The Al concentration in the reservoir sediments of Bugri, Kumpalgogo and Doba were greater than that in their contributing catchments, although the differences were not significant. The variations in the Al concentrations in the reservoir sediments were greater than that of the catchments. A significant positive correlation between reservoir sediment clay and Al was recorded. The implication is that as the clay content increases, the Al also increases. This may be because of the fixation of Al by clay.

Exchangeable cation ratios

The levels of exchangeable cations in a soil are valuable in advisory work on soil fertility, as they do not only indicate the existing nutrient status, but also can be used to access balances among cations. Many effects on soil structure and nutrient uptake by crops, for example, are influenced by the relative concentrations of cations, as well as their absolute levels. Thus, the Ca:Mg and K:Mg ratios were calculated in this study to facilitate the assessment of critical values for availability and uptake by crops.

Calcium:Magnesium (Ca:Mg) ratio

The Ca:Mg ratios of the catchment soils ranged from 5.27 to 8, with a mean value of 6.8 (Table 4). The values for the Bugri, Dua and Doba catchments were significantly greater than those for Zebilla and Kumpalgogo. In contrast, the reservoir sediments exhibited lower values, being in the range of 2.41 and 7.81, and a mean value of 4.85 (Table 5). According to Landon (1991), the approximate optimum range for most crops is 3–4. Magnesium becomes increasingly unavailable, and at high pH, P availability may be reduced with increasing Ca, as the ratio becomes ≥5. At ratios <3, P uptake may be inhibited, with a ratio of 1.0 being considered the lowest acceptable limit at which Ca availability may be slightly reduced. These ranges must be considered in assessing nutrient deficiency symptoms, and for managing the catchment soils for fertility and productivity, given that their Ca:Mg ratios were >5.

The recycling of the nutrient-rich sediment, which may be dredged from the reservoirs as a soil fertility amendment in the catchments, could enhance the productivity of the catchment soils. The Ca:Mg and K:Mg ratios, and their implications for soil fertility and nutrient uptake by plants, however, must be assessed and appropriate management practices adopted when reservoir sediments are used as a soil amendment.

Potassium:Magnesium (K:Mg) ratio

The K:Mg ratios in the catchment soils varied between 0.29 and 9.66 with a mean value of 3.91 (Table 4). The variability in the ratios among the catchments (CV = 85.3%) was very high. The ratios of the reservoir sediments, which ranged from 0.32 to 0.82, with a mean value of 0.61, were lower than those of the catchment soils (Table 5). According to Landon (1991), a ratio >2 may inhibit Mg uptake. Accordingly, recommended values are <1.5 and 1.0 for field crops and vegetables, respectively.

Nutrient enrichment ratios of reservoir sediments

Assessment of the nutrient concentrations indicated that the reservoir sediments were richer not only in nutrients, but also clay and silt, than the catchment soils. This is consistent with several studies on fertility erosion in Ghana and other parts of the world. (Quansah *et al.* 2000; Haregeweyn *et al.* 2008).

The enrichment ratio (ER), which is the ratio of the nutrient concentration in the eroded sediment to that in the original soil, is a measure of the magnitude of nutrient richness (Haregeweyn *et al.* 2008). It is also an indicator of the selective removal of the finer, more fertile fraction of the soil subject to erosion. The importance of, but also scarcity of data on enrichment ratios in the savanna zone of Ghana underscored the need for calculation of enrichment ratios for organic carbon, total nitrogen, available phosphorus, potassium, calcium, magnesium, clay and silt (Table 8). All enrichment ratios greater than unity indicate the eroded sediments in the reservoirs are richer in all soil fertility constituents except potassium, which was richer only in Zebilla and Dua Reservoir.

The enrichment ratios ranged from 1.08 to 2.96, 0.73 to 4.58, 0.63 to 1.96, 0.12 to 6.44, 1.31 to 5.94 and 1.96 to 6.29 for OC, N, P, K, Ca and Mg, respectively. The ratios varied from 3.86 to 12.61 for clay, and 1.6 to 4.84 for silt. The enrichment ratios confirm the selectivity of the sediment transport process to remove finer particles, which are relatively high in plant nutrients and organic matter.

As indicated by Menzel (1980), enrichment ratios are important, not only from the perspective of depletion of soil fertility, but also for predicting the effects of soil erosion and erosion control practices on water quality. Thus, any soil management practice in the catchment areas of the reservoirs that reduces soil loss, run-off, nutrient and organic matter loss has the potential to maintain the fertility and productive capacity of the soils for sustainable agricultural production. However, while the promotion of catchment area protection and soil and water conservation is the preferred option for maintaining catchment ecosystem integrity, the potential of using the rich reservoir sediments for reclaiming degraded land merits further study. It is important that the heavy metal, pollutant and pathogen contents of the desilted sediments be ascertained through further research studies before they are used as soil amendments.

A positive outcome will serve as great motivation for local communities to dredge and use the sediments for rehabilitation of their land, utilizing their own labour, especially where the drying up of the reservoirs makes such activities feasible. This practice would decrease the cost of rehabilitation and also increase the useful life of the reservoirs.

Table 8. Enrichment ratio of nutrients and soil textures from five study catchments in the Upper East Region of Ghana

Reservoirs	OC	N	P	K	Ca	Mg	Sand	Clay	Silt
Dua	1.08	0.73	1.73	1.25	2.22	3.67	0.31	8.21	4.84
Doba	1.45	1.16	1.52	0.87	1.98	6.29	0.81	3.86	1.6
Zebilla	1.53	4.58	1.24	6.44	5.94	5.82	0.34	12.61	5.3
Kumpalgogo	2.96	2.13	1.96	0.31	1.31	1.98	0.34	4.32	4.54
Bugri	1.937	1.83	0.63	0.12	1.62	1.96	0.28	5.27	2.96
Average	1.79	2.09	1.42	1.80	2.61	3.94	0.42	6.85	3.85

OC, organic carbon; N, total nitrogen; P, available phosphorus; K, potassium; Ca, calcium; Mg, magnesium.

Nutrient export from the reservoir catchments

The nutrients exported from the catchments are sediment-bound, in contrast to the nutrients being in solution. All indications are that these nutrients are transported into the reservoirs by catchment-generated run-off. The calculated nutrient export (NE) rates are presented in Table 9.

The average export rates (kg ha^{-1} $year^{-1}$) were 0.755 (±0.264) for OC, 0.104 (±0.0245) for N, 0.0020 (±0.0003) for P, 0.016 (±0.0038) for K, 0.009 (±0.0024) for Na, 0.113 (±0.017) for Ca and 0.027 (±0.0093) for Mg.

Table 9. Nutrient export rates for five study catchments in the Upper East Region of Ghana

	OC	N	P	K	Na	Ca	Mg
Reservoirs				kg ha^{-1} $year^{-1}$			
Dua	0.609	0.055	0.00357	0.0296	0.0188	0.2205	0.0493
Doba	0.27	0.0173	0.00043	0.0066	0.00197	0.0292	0.0128
Zebilla	0.371	0.0692	0.00077	0.0067	0.00347	0.1111	0.0206
Kumpalgogo	2.237	0.3466	0.00483	0.0313	0.0163	0.1723	0.0492
Bugri	0.288	0.0299	0.00024	0.0032	0.00213	0.0339	0.005
Average	0.755	0.104	0.0020	0.016	0.009	0.113	0.027
s.e.d.	0.2644	0.0245	0.0003	0.00381	0.00243	0.01697	0.0093
CV(%)	42.9	29	20.3	30.2	34.8	18.3	41.70

OC, organic carbon; N, total nitrogen; P, available phosphorus; K, potassium; Na, sodium; Ca, calcium; Mg, magnesium; s.e.d., standard error difference; CV, coefficient of variation.

There is limited data on OC and nutrient export rates in Ghana and other parts of sub-Saharan Africa. Yet, the extent of nutrient depletion in Ghana through erosion is widespread in all agro-ecological zones in the country, with N and P being the most deficient nutrients. Stoorvogel and Smaling (1990) estimated the annual nutrient depletion rate in Ghana from erosion and other loss pathways to be 30 kg N, 3 kg P and 17 kg K ha^{-1}in 1982–1984. The projected figures for year 2000 were 35 kg N, 4 kg P and 20 kg K ha^{-1}. Available data from bare run-off plots in the Sudan savanna zone (Bonsu & Obeng 1979), the location of the present study, exhibited sediment-bound nutrient export rates (kg ha^{-1} $year^{-1}$) of 1.79, 19.87, 34.26, 197 and 532 for N, OC, OM, available P and K, respectively. These authors, however, demonstrated that the type of tillage system and cropping system significantly impacted the magnitude of the nutrient export. For a range of cultivation practices, intercropping and manuring with farmyard manure, the NE rates (kg ha^{-1} y^{-1}) ranged from 0.069 to 2.26 for N, 1.38 to 43.71 for OM, 0.80 to 25.35 for OC, 136 to 162 for available P and 218 to 818 for available K.

These values are several orders of magnitude higher than those reported in this study for the various catchments. The relatively small run-off plot size from which these calculations were derived vis-a-vis the large catchments in this study, with varying land cover, topography, hydrology and land use, among other factors, may account for the observed variations. The low nutrient levels in the catchment soils in this study may also partially account for the observed low nutrient export rates. Furthermore, reservoir catchment studies by Haregeweyn *et al.* (2008) in Northern Ethiopia indicated sediment-bound nutrient export rates (kgl ha^{-1} $year^{-1}$) to be 11.56, 0.63, 97.11, 3.85, 140.97 and 2.11 for N, available P, OC, K, Ca and Mg, respectively. These latter values are also higher, compared to those determined in this study. It must be pointed out that apart from erosion being responsible for nutrient depletion, other factors, including harvested products, crop residues, leaching, gaseous losses, can result in nutrient depletion.

Association of nutrient export (NE) and specific sediment yield (SSY)

The sediment nutrient export rates were correlated with area-specific sediment yield for the five study catchments, with the results summarized in Figure 3. The results indicate a significant correlation in all cases, with R^2 values of 0.82, 0.73, 0.92, 0.98, 0.83, 0.66 and 0.86 for OC, N, K, P, Na, Ca and Mg, respectively.

From the various relationships established in this study, the nutrient export and area-specific sediment yield exhibit a positive relationship (i.e., an increased SSY leads to an increased NE).

These relationships also indicate that soil erosion and sediment transport are very important processes, and pathways that control the quantities of nutrients delivered to the reservoirs, as also reported by Garbrecht and Sharpley (1993) and Sharpley *et al.* (2000).

The relationships between SSY and the corresponding NE can be useful predictive tools, in terms of estimating the quantity of plant nutrients actually lost from the catchments and stored in the reservoir sediments.

The coefficient of determination (R^2) obtained for NE relating to SSY is significant, ranging from 0.66 to 0.988. This is similar to the values reported by Haregeweyn

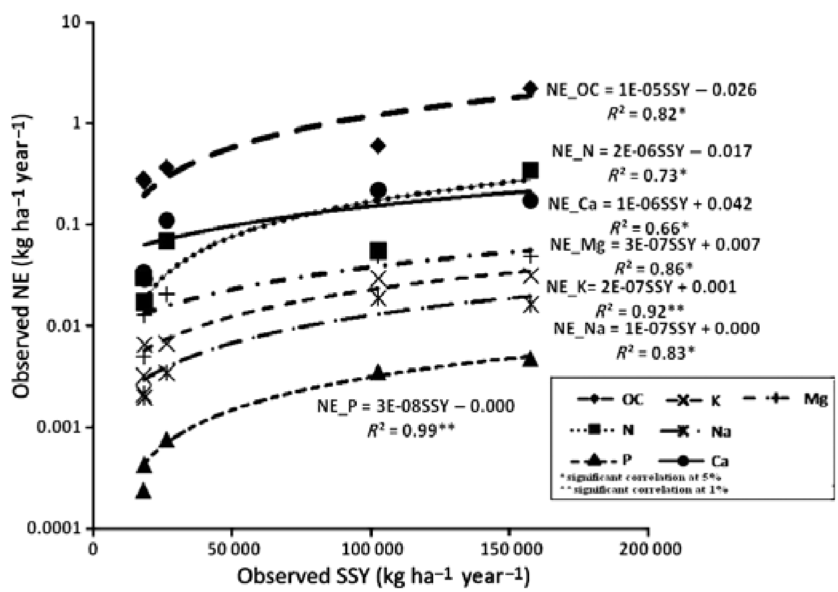

Fig. 3. Relationship between area specific sediment yield (SSY) and nutrient export (NE) rates.

et al. (2008) in Tigray, Ethiopia, where the R^2 ranged from 0.29 to 0.95. The implication is that SSY accounts for between 66% to 98.8% of the variations in the calculated NE. Thus, the equations in Figure 3 can be satisfactorily used to predict NE from the catchments, if the SSY value is known. It must be pointed out that as the equations are empirical, they are mainly valid for catchments with the same characteristics as those in this study.

CONCLUSIONS

Soil loss through erosion reduces the nutrient stocks in catchment soils. After several years of erosion, the current nutrient concentration of the catchment soils has been established as a means of not only monitoring future trends in declining soil fertilityç but also for selecting appropriate soil amendments for improved productivity.

Differences in soil type, topography, rainfall-run-off characteristics, crop cover, organic matter content of soils and soil management practices, among other factors, can result in considerable spatial variability in the nutrient content of the various catchment soils and reservoir sediments.

This study confirms the selective nature of the sediment transport process, as illustrated by ER values (>1) of 1.79, 2.09, 1.42, 1.80 2.61, 3.94, 6.85, 3.85, 0.42 for OC, N, P, K Ca, Mg, clay, silt, and sand, respectively. The sediment-nutrient-bound export rates for various nutrients have been established for representative catchments of five small reservoirs in Ghana. Nutrient export rate (NE) correlates significantly and positively, with specific sediment yield (SSY), meaning the NE increases as the SSY increases. Empirical equations relating NE to SSY indicated R^2 values ranging from 66–98.8%. Thus, SSY accounts for 66–98.8% of the observed variations in NE. The equations may be used satisfactorily to predict annual nutrient export rates for similar catchments in the Upper East Region and elsewhere.

Sediments, organic materials and nutrients transported from watersheds to reservoirs are a primary cause of water quality degradation. These pollutants pose a potential threat to human and livestock health, cause decreased reservoir volume because of sedimentation and result in lost user benefits. Catchment area protection is needed to control erosion from the catchments and to reduce both on-site (fertility and productivity loss) and off-site (sedimentation and pollution) impacts of erosion. These measures may include adopting appropriate soil and water conservation practices, such as afforestation, improved vegetative cover with recommended cover and forage species, sustainable land management practices, and vegetative barriers (vetiver) around reservoirs. Desilted nutrient-rich sediments could be used as a soil amendment to improve the productivity of catchment soils. This possibility will require field experimentation to ascertain the benefits of these sediments in enhancing crop yields and biomass production. However, the heavy metal, pollutant and pathogen contents of the desilted sediments must be ascertained through further studies before they are used freely as soil amendments.

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