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Assessing sediment inputs to small reservoirs in Upper East Region, Ghana

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Abstract

Many small dams and dugouts have been constructed in the Upper East Region of Ghana to address the problem of regional water scarcity. The reservoirs were constructed primarily as water supplies for agricultural irrigation and livestock watering, aquaculture and domestic use. However, many of the reservoirs dry up during the dry season, affecting the livelihoods of their basin inhabitants. A major cause for the dried reservoirs is siltation, which reduces the reservoir's storage capacities. The goal of this study is to quantify the annual siltation rate of four study reservoirs, using a bathymetric survey and reservoir soil sampling. The sediment yield and its relation to catchment area also were assessed. The results of this study indicate that the annual siltation rates are 1272, 3518, 2764 and 6135 t year^{-1} for Doba, Dua, Zebilla and Kumpalgogo reservoirs, respectively. Analyses of the sediment yield and catchment areas illustrated that the sediment yields decreased with increasing catchment area. All the study reservoirs have lost their dead storage capacity, which was meant to store sediment until the end of their anticipated design lives. The decreasing storage capacity because of siltation will affect the livelihoods of the local basin inhabitants, as the reservoirs will not be able to achieve all their intended purposes. The results of this study indicate that, because siltation is not the only factor threatening the benefits gained from the reservoirs, the integrated assessment of all relevant factors is required.

Key words

bathymetric survey, Ghana, sediment yield, siltation, small reservoirs.

INTRODUCTION

Although fresh water is a basic requirement for all forms of life, as well as vital for human survival, health and dignity, and a fundamental resource for human development, many areas of the world nevertheless experience serious shortages in water resources, mainly because of changes in climate and human activities. An example is the Upper East Region of Ghana, which experiences low and erratic precipitation, leading to water scarcity in a region in which the inhabitants are dependent primarily on rain-fed agriculture for their sustenance and economic livelihoods. To reduce the impacts of drought in this area, the Government of Ghana and various donor agencies have constructed more than 200 small dams and dugouts over the past 50 years. Most of the reservoirs were constructed in the 1960s, and the number continues to increase because the reservoirs are a means of extending the initial single cropping season existing before the reservoirs, to multiple cropping seasons after their construction, thereby working to reduce the region's poverty (Birner *et al.* 2005). These reservoirs capture run-off during the rainy season, making it available during the dry season, when the natural water bodies are dried up. Water from the reservoirs is used mainly for agricultural irrigation, domestic water supply and livestock watering and aquaculture. It also is used for recreation and construction. These reservoirs, therefore, contribute to reducing the vulnerability of their basin inhabitants to drought and to improving their livelihoods. The reservoirs also have a significant effect on downstream flows, as they can provide a buffer from flooding by delaying and diminishing flash floods by temporarily storing the excess water (Poolman 2005). They also help recharge groundwater aquifers, thereby increasing the base flow in

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the downstream part of the catchment area. This stabilizes the water supply to downstream wells and reduces siltation of Akosombo Reservoir by trapping the sediments entering it (IFAD (International Fund for Agricultural Development) 1999).

The sustainability of the reservoirs, however, is being challenged by problems directly affecting the economic livelihoods and economic development of their basin inhabitants. Many of the reservoirs dry up in the dry season, for example, resulting in reduced or total loss of the aforementioned benefits. There is a perception that the drying up of the reservoirs is caused by siltation, which has resulted in a reduced reservoir water storage capacity. In fact, a community-needs assessment study by Gyasi and Schiffer (2005) revealed that the majority of the communities complained of siltation of their dams.

The consequences of soil erosion and sediment deposition occur both on- and off-site. On-site effects are experienced on agricultural lands, whereby soil loss from a field leads to a decline in organic matter and nutrients, resulting in a reduction of the cultivable soil depth and decreased soil fertility. The net effect is a loss of productivity of the agricultural land (Pimentel *et al.* 1995). Off-site problems result from downstream sedimentation, which reduces the reservoir capacity, enhances flooding risks and the occurrence of muddy floods and shortens the reservoir design life (Verstraeten & Poesen 1999). Information on a drainage basin's sediment yield is an important requirement for water resources development, catchment management and soil and water conservation. Sediment yield data are very limited for the Volta River Basin of Ghana, however, primarily because of limited logistical support for data collection (Akrasi 2005).

Reservoir sedimentation studies by Tamene (2005) in Tigray, Ethiopia, indicated area-specific sediment yields ranging from 3 to 49 t ha^{-1} $year^{-1}$, with a mean value of 19 t ha^{-1} $year^{-1}$.

This mean sediment yield of 19 t ha^{-1} $year^{-1}$ was higher than the mean global (15 t ha^{-1} $year^{-1}$) and African (9 t ha^{-1} $year^{-1}$) sediment yield rates. Studies conducted by NEDECO (1997) also reported sediment yield ranges from 1.4 to 33 t ha^{-1} $year^{-1}$ for different basin sizes ranging from 15 to 70 000 km^2. Machado *et al.* (1995) estimated an annual sediment yield of 21 t ha^{-1}, based on an in-filled dam with a catchment area of 6.7 km^2 on one of the Tekezze River tributaries in the Tigray region of Ethiopia. The variation in sediment yields in these studies, as well as many others, can be attributed to the biophysical characteristics of the reservoir catchments, as well as anthropogenic reasons. The latter include, but are not limited to, the nature of slopes, land use patterns, catchment size and methods of measurements (Tamene *et al.* 2006).

Thus, the objectives of this study are to: (i) quantify the annual siltation rate, utilizing bathymetric surveys, and (ii) assess the relationship between sediment yield and catchment area for four small reservoirs in the Upper East Region of Ghana.

Because of time constraints, and limited logistical and financial resources, it was not possible to study all the reservoirs in the region that exhibited siltation problems. Thus, it was necessary to select sites representative of the region's catchments, based on their spatial distribution, geology, soil and catchment size.

METHODS

Study site

This study was carried out on four representative small reservoirs in the Upper East Region of Ghana. Their characteristics are given in Table 1. The Upper East Region is the northeasternmost 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), and contains eight administrative districts (Bolga, Bongo, Builsa, Kasena-Nankana, Talensi Nandam, Bawku West, Bawku East, Garu Tempani; Fig. 1). According to the 2000 population and housing census (GSS, 2005), the region has a population

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

Site	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

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, dam wall height (m); SE, spillway elevation (m); CE, dam crest elevation (m) ; N/A, not available.

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

of 920 089, including 442 492 men and 477 597 women. The region has a comparatively high population density of 104.1 persons km^{-2}, compared with the national average of 79.3 persons km^{-2}, attributable to the comparatively favourable soil conditions in parts of the region. The population of the region is ethnically diverse, comprising different ethnic groups that speak different languages (Birner *et al.* 2005), and among the poorest regions in the country (Asenso-Okyere *et al.* 2000). Over 80% of the population live in rural areas, with agriculture comprising their major economic activity (Birner *et al.* 2005). The region falls within the Intertropical Convergence Zone, whose climatic boundary oscillates annually between the south coast of Ghana and 20° north. As the boundary moves north and south, it encounters the associated weather zones. The effect of this oscillation on the region is a unimodal rainfall regime lasting 5–6 months, and which is characterized by low, erratic rainfall and a dry period of 6–7 months. Considerable variations exist between successive rainy seasons, with regard to the time of onset, duration and quantity of rainfall received (Walker 1962). The average annual rainfall in the region is ≈1100 mm (Faulkner 2006), with a high percentage of the total rainfall occurring as thunderstorms. As a result, the rainfall intensities often exceed the soil infiltration rates, leading to surface runoff (Liebe *et al.* 2005). The temperatures are consistently high, with an average of 28.6 °C. The average annual relative humidity is 55%. There is a high variability in the temperature and relative humidity, thereby resulting in high evapotranspiration levels, which might affect the drying of the reservoirs. The vegetation in the region is Sudan savanna, consisting of short drought- and fire-resistant deciduous trees, interspersed with open savanna grassland. The grass is very sparse, with most areas exhibiting bare, severely eroded soils. The soils (Fig. 2) in the area are generally formed by weathering of the bedrock, although some drift of soil via wind and water transport is also observed. The soils comprise Luvisols, Cambisols, Gleysols, Regosols, Vertisols, Plinthosols and Fluvisols developed from granites, Birimian rocks and alluvia of mixed origin (Quansah 2005). 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. 3). A substantial band of sandstone, grit and conglomerate parallels the boundary, and the course of the White Volta, in the southeastern boundary area of the region. There are small areas of intrusive diorite in the northwestern portion of the region. Laterite has been formed by fluvial processes in the flatlands adjacent to present and past water courses, occurring over large areas. Sand occurs as local deposits along most of the major river courses.

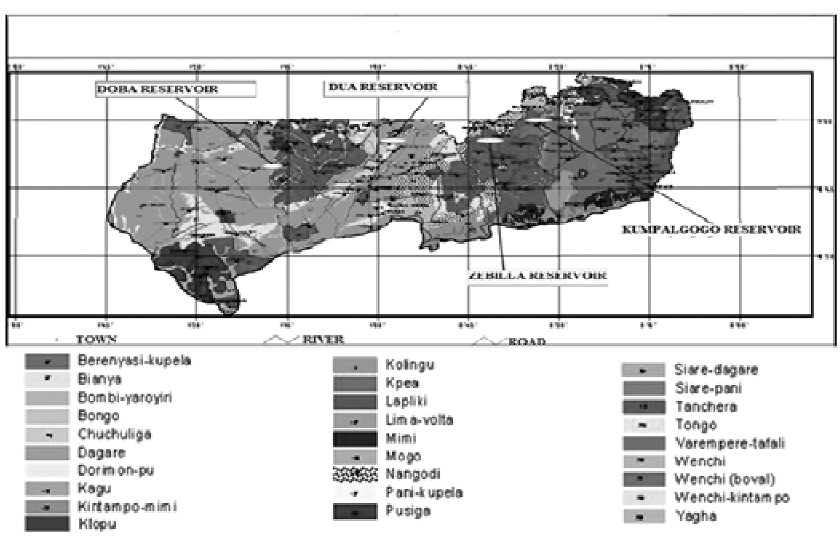

Fig. 2. Soil map of Upper East Region, Ghana, showing study sites[Boateng, 2008].

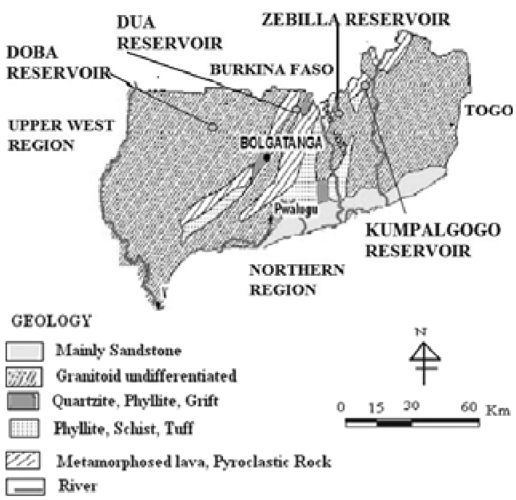

Fig. 3. Geology map of Upper East Region, Ghana, showing study sites [Kesse, 1985].

Site selection

Four reservoirs were selected for the study on the basis of the following criteria:

- dugouts and desilted reservoirs were omitted;
- the size of the reservoir was considered (small, medium, big);
- reservoirs with design maps, and which were rehabilitated between 1990 and 1998 were considered.

Bathymetric surveys

For the bathymetric surveys, information on the original reservoir capacity is required as a benchmark against which the present water storage capacity can be compared (Rausch & Heinemann 1984). Information on the initial reservoir storage capacity was obtained from the Irrigation Development Authority (IDA) in Bolgatanga (Regional Capital). Bathymetric surveys were conducted from 20 September to 2 October 2007 to derive the current water storage capacity of the four study reservoirs. A boat, equipped with a Lawrance LMS 480 Fish-Finding Sonar and Global Positioning System (GPS) device, was used to conduct the surveys. The boat equipment measures depth, with a transducer fitted on the boat, recording the geographic position of the transducer with a GPS receiver. To account for the spatial variability of sediment deposition within the reservoirs, more than 800 points covering the water surface were collected for each reservoir. The periphery and elevation of the water surface for each reservoir were measured with handheld GPS and automatic levelling instruments, respectively. These data were analysed using Golden Software Surfer 8. The elevation of the current reservoir bed (i.e. top of sediment) at each measurement point was defined by deducting the recorded depth from the water surface level, as measured with automatic levelling instrument. Reservoir water storage capacity and surface area were calculated for each 1 m interval, using the Surfer's 'Volume' function. The current capacity curves of the reservoirs were constructed on the basis of these calculations. The total volume of sediment deposition was then calculated by subtracting the current water storage capacity from the initial water storage capacity.

Determination of sediment dry-bulk density

Undisturbed sediment samples were collected from the four reservoirs with a beeker sampler. Five sediment samples were collected from each reservoir. The samples were oven-dried at 105 °C for 24 h to determine their dry bulk densities. The mean dry-bulk density (ρ_b) of each group of samples (Table 2) was used to calculate the sediment mass.

Estimation of reservoir trap efficiency

The trap efficiency (TE) is the ratio of the sediments retained in reservoir, compared with the total sediment brought in the reservoir (Anyemedu 2007). To determine the average sediment yield from the contributing watersheds, the weight of deposited sediment must be adjusted for the reservoir sediment TE. The calculation proposed by Brown (1943) was used to estimate the TE of the reservoirs, as follows:

$$\mathrm{TE} = 100\left(1 - \frac{1}{1 + 0.0021D\left(\frac{\mathrm{SC}}{A}\right)}\right), \tag{1}$$

where SC is the reservoir design storage capacity (m^3); A is the catchment area (km^2); D is a coefficient with

Table 2. Parameters used to calculate catchment sediment yields

Site	A (ha)	SC (10^3 m^3)	Age (years)	ρ_b (t m^{-3})	TE (%)
Doba	70	178.0	9	1.64	98.16
Dua	35	76.3	10	1.51	97.86
Zebilla	105	434.9	9	0.99	98.86
Kumpalgogo	40	80.8	9	1.41	97.70

A, catchment area; SC, storage capacity; ρ_b, dry-bulk density; TE, sediment trap efficiency.

values ranging from 0.046 to 1 and a mean value of 0.1 (Brown 1943). The value of TE depends on D, which also depends on a reservoir's characteristics. Considering the difficulty in objectively defining the value of D, the mean value of 0.1 was used in the calculations.

Calculation of catchment sediment yield to reservoirs

The siltation rate, annual sediment yield and area-specific sediment yields were calculated as follows:

$$\mathrm{RS} = \frac{\mathrm{SV} \times \rho_b}{Y}, \tag{2}$$

$$\mathrm{SY} = 100\frac{\mathrm{SV} \times \rho_b}{\mathrm{TE} \times Y}, \tag{3}$$

$$\mathrm{ASY} = \frac{\mathrm{SY}}{A}, \tag{4}$$

where RS is the rate of siltation (t year^{-1}); SY is the sediment yield (t year^{-1}); ρ_b is the dry-bulk density (t m^{-3}); TE is the trap efficiency (%); Y is the age of the reservoir (years); SV is the sediment volume (m^3); ASY is the area-specific sediment yield (t ha^{-1} year^{-1}); and A is the catchment area (ha).

RESULTS AND DISCUSSION

Sediment deposition in reservoirs

The siltation rates, sediment yields and area-specific sediment yields for the four study reservoirs are summarized in Table 3. The mean area sediment yield (76 t ha^{-1} year^{-1}) obtained in this study was of a similar order of magnitude as those observed by Tamene (2005; 19 t ha^{-1} year^{-1}) and Machado *et al.* (1995); 21 t ha^{-1} year^{-1}) in related sedimentation studies. The values and ranges obtained in this study, however, were higher compared with the other studies. In comparing the sediment volume results with dead-storage capacities (see Table 1), it is determined that all the reservoirs have lost more than 100% of their dead storage, which is designed to store sediment until the end of their anticipated design lives.

The rate of sediment deposition for the four reservoirs indicates that the live storage of the reservoirs will not be filled up before the end of their design lives of 25 years. However, the design storage capacity is significantly affected. Table 4 illustrates the percentage of design storage capacity the reservoir has lost to the present time and after the design life. Although the percentages of the current storage capacity already lost for Doba and Zebilla Reservoirs were not sufficient to cause the reservoirs to dry up, those for Dua and Kumpalgogo Reservoirs can account for their drying up.

Table 3. Sediment deposition rates for study reservoirs

Site	RS (t year^{-1})	SY (t year^{-1})	ASY (t ha^{-1} year^{-1})
Doba	1271.50	1295.32	18.50
Dua	3517.50	3594.50	102.70
Zebilla	2764.38	2801.22	26.68
Kumpalgogo	6135.02	6279.74	156.99

RS, siltation rate; SY, sediment yield; ASY, area-specific sediment yield.

Table 4. Current and projected storage capacity lost

Site	Age (years)	Current capacity lost (%)	Projected capacity lost at 25 years† (%)	Useful reservoir life (years)
Doba	9	3.78	10.51	190
Dua	10	23.36	58.41	34
Zebilla	9	5.46	15.18	132
Kumpalgogo	9	32.71	90.86	22

†Reservoir design life is 25 years.

Doba and Zebilla Reservoirs will lose only up to about 10.5 and 15.2% of their storage capacities by the end of their respective design lives. However, Kumpalgogo Reservoir, with a higher rate of sediment deposition, will lose up to about 90.9% of its storage capacity by the end of its design life. Anyemedu (2007) stated that the useful life of the reservoir is terminated when its storage capacity is reduced to 20% of its design capacity. From the calculations of the useful lives for the four study reservoirs, Kumpalgogo Reservoir will not meet its objectives until the end of its design life because of its high rate of siltation. The remaining reservoirs might still be in use, however, based on the assumption that factors influencing their sedimentation will remain the same, and with an unchanged sedimentation rate.

The decreasing storage capacities for all the study reservoirs related to siltation, however, will have an effect on the livelihoods of the local inhabitants. As the reservoir capacity decreases, the reservoirs will not be able to accommodate their intended uses. Increasing human and animal populations in their basins, coupled with their decreasing storage capacity, means that the reservoirs would have to be used below their intended yields. This implies that the local basin inhabitants might have to stop dry season farming to maintain water supplies for other critical uses, such as livestock watering and domestic consumption.

Factors influencing estimations of sediment yields

The sediment yield was determined on the basis of the volume of the reservoir occupied by the sediment, its dry bulk density, sediment trapping efficiency and the age of the dam. Estimation of these factors, especially the sediment volume, might introduce errors which will eventually affect the sediment yield results.

The results of sediment retention on the reservoir bathymetry are based on a comparison of the storage capacities at different periods. The reservoir capacity in this study was compared with the initial design capacity to determine the sediment volume. To determine the current reservoir capacity, the water elevation was defined by transferring water heights from known benchmarks. Because all located benchmarks did not have elevation values, their values had to be interpolated from contour maps, which could lead to errors in the final results if the benchmarks had slight dislocations. In fact, as the communities farm around the reservoirs, most benchmarks had been removed. Design maps obtained from IDA were produced before construction of the dams. If the area in which the dam was constructed had suitable material, the contractor might have decided during the construction phase to burrow that material to use in constructing the dam wall. This will have resulted in changes in the area–capacity curves after the construction that were not reflected in the design drawings. Further, because the spillway elevation might not be constructed exactly as provided in the design drawings, slight changes in the elevation during dam construction could change the original storage capacity value. All these changes could affect the accuracy of the sediment volume estimation.

During field studies, it also was recognized that community members could have excavated soil around some reservoirs (e.g. Doba) to mould blocks and bricks for construction in the dry season. The reservoir bed material is excavated when dry for the same purpose. This activity tends to increase the reservoir capacity, meaning the sediment volume results might not accurately define the reservoir sediment volumes.

Different interpolation methods (e.g. density estimation, inverse distance weighting, Triangulated Irregular Networking (TIN) and Kriging) exist for estimating sediment volume, which can affect the estimation results. To illustrate the potential differences in results from different interpolation methods, the TIN and Kriging methods were tested in this study. The current estimated reservoir capacity based on the two methods is presented in Table 5. The TIN method gave higher values at a given elevation for the existing capacity, compared with the Kriging method, which could lead to differences in sediment volume estimations. Because it provided better extrapolations than TIN, the Kriging method was adapted in this study.

Table 5. Estimate of current Kumpalgogo Reservoir capacity, using TIN (Triangulated Irregular Networking) and Kriging methods

Elevation (m)	TIN (m^3)	Kriging (m^3)	Difference (m^3)
190	1611	330	1281
191	17 955	7393	10 562
192	47 142	27 768	19 373
193	91 398	80 748	10 650

The remaining factor that could affect the sediment yield results is sediment dry bulk density. For this study, five dry bulk densities (ρ_b) were estimated for each reservoir from two different depths (0–15 and 15–30 cm). The ρ_b generally decreased towards the dam wall. The soil sampled closer to the ends of the reservoir exhibited higher ρ_b values than those in the middle and close to the dam wall. The dry bulk density varies with the kind of sediment deposition and with their age. The sediment deposited in the reservoirs is not homogeneous because, as sediment travels through a reservoir, bigger particle sizes are more likely to be deposited before (i.e. close to the ends of reservoirs) the finer-sized particles, which will be deposited in the deeper part of the reservoir (Tulu 2002). This phenomenon highlights the need for multiple sampling to obtain an accurate ρ_b estimate for a particular reservoir. The mean ρ_b values are 1.64, 1.51, 0.99 and 1.41 t m^{-3} for Doba, Dua, Zebilla and Kumpalgogo reservoirs, respectively. The mean ρ_b value for Zebilla Reservoir differs significantly from that of the other reservoirs.

Sediment yield and its relation to catchment area

Sediment yield and catchment area have a negative relationship (Walling 1983). This negative relationship is attributed mainly to an increasing opportunity for sediment deposition and storage, both on the slopes of a catchment and within the channel system, as the catchment area, and sediment travel distances and times increase. Other studies by Dedkov (2004), however, have demonstrated that positive relationships can occur when channel erosion is an important sediment source. This positive relationship is attributed to increased discharges and, therefore, increased available energy for channel erosion with increasing catchment area. Thus, the relationship between the annual sediment yield and catchment area depends on the complexity and variability of associated terrain attributes (e.g. topography, land use and land cover, soils and climate). This observation highlights the need to evaluate the relationship between catchment area and sediment yield for local conditions before any derived empirical relationships can be adapted to other environments with similar settings.

The relationship between sediment yield and catchment area for the study reservoirs is presented in Figures 4 and 5. The sediment yield trends (ASY and SY) in relation to their catchment area illustrate a decreasing ASY and SY with increasing catchment size. This finding is indicated by the negative exponents associated with Equations 5 and 6, which confirm the widely held view regarding the sediment yield–catchment area relationship. Larger drainage areas lead to an increasing tendency for sediment deposition within the watershed, thereby resulting in decreasing sediment yield.

$$\log \mathrm{SY} = 3.296A^{-0.09}, \qquad R^2 = 0.31, \tag{5}$$

$$\log \mathrm{ASY} = 1.310A^{-0.43}, \qquad R^2 = 0.71. \tag{6}$$

According to De Boer and Crosby (1996), an exponential relation with an exponent of less than 1 indicates that the size of the catchment area increases faster than the sediment yield, thereby resulting in a downstream decrease in ASY. Considering this relation, and referring to Equation 5, it can be concluded that the catchment area increases faster than the sediment yield, so that the ASY decreases downstream.

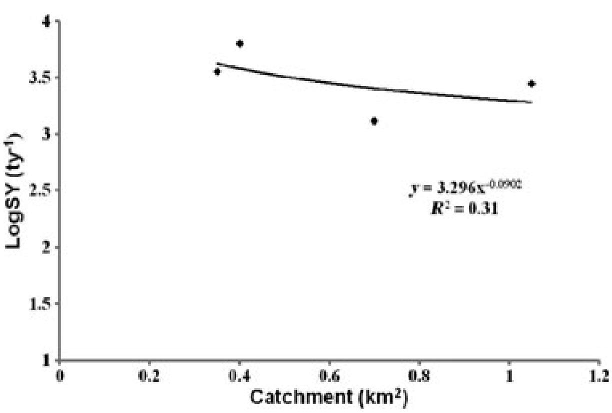

Fig. 4. Relationship between sediment yield and catchment area for study reservoirs.

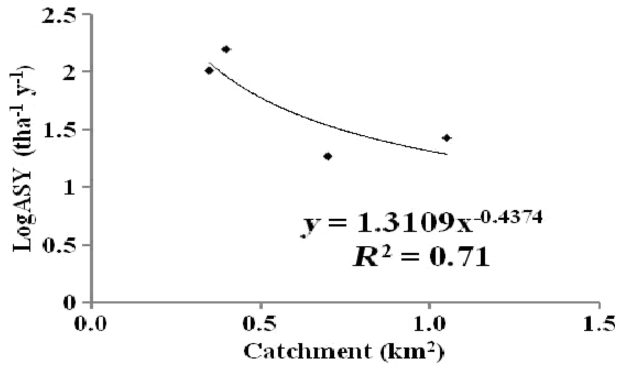

Fig. 5. Relationship between area-specific sediment yield and catchment area for study reservoirs.

The coefficient of determination (R^2) obtained for the relationship of ASY to the catchment area is higher than that for SY, implying that the catchment area had a greater influence in reducing the ASY than SY. The R^2 value for Equation 6 also means that the catchment area accounted for about 71% of the variation occurring for the ASY, whereas the remaining 29% might be because of other factors. Thus, Equation 6 can be used to estimate sediment yield for reservoirs in the area, assuming that the reservoir catchment area is known.

The reservoir bathymetric survey results indicated that the mean annual siltation rate for the reservoirs was 1272, 3518, 2764 and 6135 t year^{-1} for Doba, Dua, Zebilla and Kumpalgogo Reservoirs, respectively (Table 3). These results were used to develop a simple empirical model for predicting area-specific sediment yields from similar catchments. The estimated siltation rates indicated all the reservoirs have lost their dead storage capacities, and that the ability of the reservoirs to achieve their design yields is in question. The results also suggest that drying up of the reservoirs because of siltation, although critical for some reservoirs, might not be the only reason for the loss of reservoir volume. A combination of factors, including high evapotranspiration rates, seepage and dependency on the reservoirs for all types of water supply might be other key contributing factors.

It is obviously very important to reduce sediment deposition in the reservoirs to increase their operational life spans. Thus, it is recommended that the reservoirs be desilted, when necessary, to maintain their design storage capacities. If feasible, sediment bypassing also could be considered, especially for reservoirs with low capacity to annual inflow ratios. It is also necessary to re-survey reservoirs after their construction, to obtain an accurate initial storage capacity.

Based on this study, the following catchment area protection measures are recommended to reduce soil erosion and subsequent sediment yield to reservoirs:

- Delineate a buffer zone around reservoirs as a means of preventing farming activities close to the reservoirs.
- Grow vetiver grass around reservoirs, and in any areas exhibiting traces of erosion.
- Control livestock grazing by delineating specific grazing areas that will not contribute to soil loss to reservoirs.

At the same time, because siltation is not the only factor that can cause reservoirs to dry up, integrated assessment of all factors is also required.

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REFERENCES

Akrasi S.A. (2005) The assessment of suspended sediment inputs to Volta Lake. *Lakes Reserv.: Res. Manage.* **10**, 179–86.

Anyemedu F. O. K. (2007) Hydraulic Structures, Reservoir Engineering Lecture Notes. Water Resources Engineering and Management Programme. Department of Civil Engineering, KNUST, Kumasi, Ghana.

Asenso-Okyere W. K., Twum-Baah K. A., Kasanga A., Anum J. & Portner C. (2000) Ghana Living Standards Survey. Report of the Fourth Round (GLSS 4). Ghana Statistical Service, Accra, Ghana.

Birner R., Schiffer E., Asante F., Gyasi O. & McCarthy N. (2005) Analysis of Governance Structures for Water Resources Management in the White Volta Basin Ghana. Final Report. IFPRI, Washington DC, USA.

Boateng E. (2008) Characteristics of soils of the Upper East Region and their potential for agriculture. (eds W. A. Agyare & W. Laube) pp. 40–2.

Brown C. B. (1943) Discussion of "Sedimentation in reservoirs by J. Witzig". *Proc. Am. Soc. Civil Eng.* **69**, 1493–500.

De Boer D. & Crosby G. (1996) Specific sediment yield and drainage basin scale. In: Erosion and Sediment Yield: Global Perspectives (eds D. E. Walling & B. W. Webb) pp. 3333–8. Proceedings of the Excter Symposium, IAHS Publ. 236. IAHS Press, Wallingford, UK.

Dedkov A. P. (2004) The relationship between sediment yield and drainage basin area. In: Sediment Transport through the Fluvial System (eds V. Golosov, V. Belyaev & D. E. Walling) pp. 197–204. IAHS Press, Wallingford, UK.

Faulkner J. W. (2006) Water use, productivity, and profitability of small scale irrigation schemes in Ghana's Upper East Region (MSc Thesis). Cornell University, Ithaca, NY.

GSS (2005) 2000 Population and Housing Census of Ghana. Ghana Statistical Services, Accra, Ghana.

Gyasi O. & Schiffer E. (2005) Community Needs Assessment and Local Water Governance Appraisal in the Upper East Region, Ghana. Final Report Submitted to EPiD, Discussion Paper. IFPRI, Washington DC, USA.

IFAD (International Fund for Agricultural Development) (1999) Upper-East Region Land Conservation and Smallholder Rehabilitation Project – Phase II. Report and Recommendation EB 99/66/R.14. IFAD, Rome.

IFAD (International Fund for Agricultural Development) (1991) Water Resources Development, Upper East Region Land Conservation and Smallholder Rehabilitation Project. Working Paper 6. IFAD, Rome.

Kesse G.O. (1985) The Mineral and Rock Resources of Ghana. Balkema, Rotterdam.

Liebe J., Van de Giesen N. & Andreini M. (2005) Estimation of small reservoir storage capacities in a semi-arid environment: A case study in the Upper East Region of Ghana. *Phys. Chem. Earth* **30**, 448–54.

Machado M. J., Pérez-Gonzalez A. & Benito G. (1995) Reconstruccion de ambientes naturales y antropicos en la region de Axum (Tigray, Norte de Etiopia). In: Reconstruccion de paleoambientes (eds T. Aleixandre & A. Pérez-Gonzalez) pp. 163–74. Monogratia N°, CSIC.

NEDECO (1997) Tekeze River Basin Integrated Development Master Plan Project. Second Phase Report, Vol. ENV 1 – Land Degradation and Soil Conservation. Netherlands Engineering Consultants, Amsterdam.

Pimentel D., Harvey C., Resosudarmo P. *et al.* (1995) Environmental and economic costs of soil erosion and conservation benefits. *Science* **267**, 1117–23.

Poolman M. I. (2005) Developing small reservoirs: A participatory approach can help (MSc Thesis). Technical University of Delft, The Netherlands.

Quansah C. (2005) Oncho Transborder Project, Burkina Faso and Ghana. Natural Resources Use and Management Report. GCP/RAF/367/BEL, FAO Regional Office for Africa, Accra, Ghana.

Rausch D. L. & Heinemann H. G. (1984) Measurement of reservoir sedimentation. In: Erosion and Sediment Yields: Some Methods of Measurement and Modelling (eds R. F. Hadley & D. E. Walling) pp. 179–200. Geo Books, Norwich, UK.

Tamene L. (2005) Reservoir siltation in Ethiopia: Causes, source areas, and management options. In: Ecology and Development (eds P. L. G. Vlek, M. Denich, C. Martius, C. Rodgers & N. van de Giesen) Series No. 30, pp. ?????–?????. Cuvillier Verlag, Göttingen, Bron, Germany.

Tamene L., Park S. J., Diakau R. & Vlek P. L. G. (2006) Analysis of factors determining sediment yield variability in the highlands of north Ethiopia. *Geomorphology:* **76**, 76–91.

Tulu T. (2002) Soil and Water Conservation for Sustainable Agriculture. Mega Publishing Enterprise, Addis Ababa, Ethiopia.

Verstraeten G. & Poesen J. (1999) The nature of small-scale flooding, muddy floods and retention pond sedimentation in central Belgium. *Geomorphology* **29**, 275–92.

Walker H. O. (1962) Weather and climate. In: Agriculture and Land Use in Ghana (ed. J. B. Wills) pp. 7–28. Oxford University Press, England.

Walling D. E. (1983) The sediment delivery problem. *J. Hydrol.* **65**, 209–37.