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SUSPENDED SEDIMENT TRANSPORT INTO A WATER SUPPLY RESERVOIR IN SOUTHERN GHANA

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Abstract

Weija reservoir on the Densu river serves as a source of water supply to parts of Greater Accra and Central regions of Ghana. The Densu river basin is characterised by accelerated land degradation. A number of Integrated Water Resources Management (IWRM) interventions have been implemented in the basin. Reports suggest there have been improvement of physico-chemical parameters of the water resources. However, there is no recent study on fluvial sediment transport in the basin. This paper assessed sediment transport into the Weija reservoir via the Densu river. Weekly suspended sediment concentration, and river discharge were monitored over a 1 year period to quantify sediment yield into the reservoir. The results indicated that total annual suspended sediment yield, and annual specific suspended sediment yield were 5375 t yr^{-1} and 2.0 t km^{-2} yr^{-1}, respectively. These were relatively low compared to results obtained by past studies on the Densu basin at upstream Mangoase (6146 t yr^{-1} and 2.49 t km^{-2} yr^{-1}) and other river basins in Ghana. Parameters established from a yield rating curve indicated that parts of the basin were degraded and sediment transport in the basin was largely due to availability of sediment in the catchment and not just due to high river discharges. The relatively low sediment transport at Weija may be indicative of the success of the IWRM interventions. It is recommended that these be sustained and/or intensified.

Introduction

Sediment generation and transport processes in a river basin are major challenges for water managers. This is because availability of sediments in the river basin, and the sediment transport capability of a basin shorten the useful lives of water facilities such as reservoirs in the basin. Additionally, the presence of suspended sediments in reservoirs is an important environmental concern, since the suspended sediments act as attachment sites to some water quality constituents including pollutants. Design features of most reservoirs allow for particles and silt to settle out, and the retention time allows for natural biological treatment using algae, bacteria and zooplankton that naturally live within the water column. Unfortunately, due to human activities upstream and within the catchment area of these reservoirs, the reservoirs tend to silt-up more quickly, thereby reducing the storage capacity for water supply and flood control purposes, as well as compromising the water quality.

The Weija reservoir on the Densu river (one of the coastal rivers of Ghana) serves as a source of water supply to the western and central parts of the Accra Metropolitan Area and the eastern parts of the Central Region of Ghana. The reservoir is fed by inflows from the Densu river and its tributaries. A study (WRC, 2007) conducted to prepare an Integrated Water Resources Management (IWRM) plan for the Densu basin found that, the basin is characterised by accelerated land degradation due to anthropogenic activities such as small-scale gold mining, stone quarrying and sand winning (WRC, 2007). The immediate sources of sediments into the reservoir have been attributed to intensive agriculture and rapid development of settlements in the buffer zone of the reservoir (Gandaa, verbal communication).

The Water Resources Commission (WRC) is the government institution with the mandate to regulate and manage the utilisation of water resources, and the co-ordination of policies in relation to water resources. The WRC has decentralised IWRM activities currently under administrative framework, namely River Basin Boards (RBBs) and their secretariats in six river basins including the Densu basin. The RBBs are the coordinating and management structures with oversight responsibility of developing and implementing comprehensive plans for the conservation, development, and utilisation of water resources in the respective river basins.

Although the WRC is currently under-staffed, it has made great strides in implementing IWRM interventions through water-use permitting, water-use charges, groundwater drilling licensing, public education, and recently developed the National Buffer Zone Policy (MWRWH, 2011). In the Densu basin for example, there have been deployment of military and police personnel to abate illegal mining activities. Other activities in the basin have included tree planting activities and public education programmes, aimed at protecting water resources in the basin including the Weija reservoir.

The state of water quality in the basin was assessed using a water quality index (WQI), adopted by the WRC (WRC, 2007). WRC (2007) found that, in general, there was an improvement of water quality (on average WQI value of 64, i.e. fairly good quality) from upstream to downstream of the Densu river as well as in the reservoir. The study attributed it to various IWRM activities such as, relocation of solid waste dump sites, river bank protection, and tree-planting and public awareness creation, among others being implemented in the basin. However, there are currently no similar studies on fluvial sediment. Fluvial sediment information is often essential for assessing reservoir siltation rates, suitability of water for potable purposes, impact on turbines of hydro-power stations, and also indicating river basin morphological changes. Unfortunately, there are limited studies (Ayibotele & Tuffour-Darko, 1974; MWH, 1998; Akrasi, 2008; Kusimi *et al*., 2014;) on fluvial sediment studies in river basins of Ghana particularly in the Densu basin. This situation can be partly attributed to high cost of undertaking fluvial sediment monitoring (Akrasi, 2005; Akrasi, 2008; Ofori *et a*l., 2011). Understanding the sediment discharge into a reservoir is necessary, especially for effective reservoir and basin management.

The paper, therefore, assessed fluvial sediment transport into the Weija reservoir via the Densu river at Ashalaja over a 1 year period (Sep 2012 to Aug 2013), to provide same baseline information for water resources planning and management.

Experimental

Study area

The Weija reservoir is formed on the Densu river which lies between latitudes 5° 32′30″ N and 5° 37′ 30″ N and between longitudes

0° 20′ 00″ W and 0° 25′ 00″ W (Fig. 1). The sediment monitoring point was upstream the reservoir on the Densu river at Ashalaja (5° 40′ 11″ N and 0° 21′ 22″ W) about 8.0 km (along the river) from the Weija reservoir (Fig. 1). The reservoir is the third largest in the country after lake Volta and the Bui reservoir. At normal water level [15 m above mean sea level (amsl)], the reservoir has a surface area of about 30 km^2 with a maximum storage capacity of 115 Mm^3. It receives a mean annual flow of 280 Mm^3 generated from the Densu basin (WRC, 2007).

Rainfall pattern in the basin is bi-modal. The main rainy season is from April to July with the peak in June, whilst, the minor season is from September to November. The northern part of the basin falls within the moist semi-deciduous rainforest zone with rainfall ranging between 1,500 mm and 1,650 mm. The central part of the basin falls within the transition of forest and coastal savanna zones, where rainfall ranges between 1,150 mm and 1,500 mm. The southern part of the Basin falls within the coastal savanna where rainfall ranges between 900 mm and 1,150 mm. In the coastal plains of the basin, rainfall is typically less than 900 mm.

Analysis of the temporal rainfall patterns for two periods spanning from 1961 to 1980 and 2000 to 2012 (latter decade), suggest a decline in rainfall amounts in the latter decade (mean annual rainfall is about 773 mm compared to 791 mm in first period). In addition, the mean monthly rainfall amounts are particularly slightly less during the major rainy season and slightly higher during the minor season in the latter decade compared to the first period.

Temperatures within the basin are characterised by tropical climate with uniform temperature throughout the year. Mean annual temperature ranges between 27° C and 32 °C (WRC, 2007). Mean annual potential evapotranspiration varies from 1,700 mm south of the basin to 1,500 mm north of the basin, andRelative humidity ranges from 50 per cent to 60 per cent in dry season to about 80 per cen to 90 per cent in the wet season (WRC, 2007).

Elevations range from 30 m in the lowlands to about 567 m amsl in the Akwapim range and steep ridges in the Eastern Plains (Kuma & Ashley, 2008). The basin has a dendritic drainage system. The Weija reservoir receives flows from the Densu, Nsaki and Gyei which before the construction of the reservoir were tributaries of the Densu.

Generally, the soils in the basin are well drained. The soils in the basin are predominantly forest Ochrosols and savanna Ochrosols. The forest Ochrosols are found mostly in the northern and central parts of the basin with relatively high amount of nutrients. The savanna Ochrosols are low in nutrients, particularly phosphorus and nitrogen. The dominant land use in the basin is agriculture, which includes cocoa farming, cultivation of food crops, large- and small-scale oil palm plantations and vegetable cultivation particularly in the coastal part of the basin.

Sand winning activities is prominent in the basin. Also, the buffer zone of the reservoir is subject to high anthropogenic activities, particularly the hilly areas surrounding the reservoir and quarry sites overlooking the reservoir (Fig. 3). The hilly areas are very steep and have been subjected to intensive farming, and the reservoir receives high

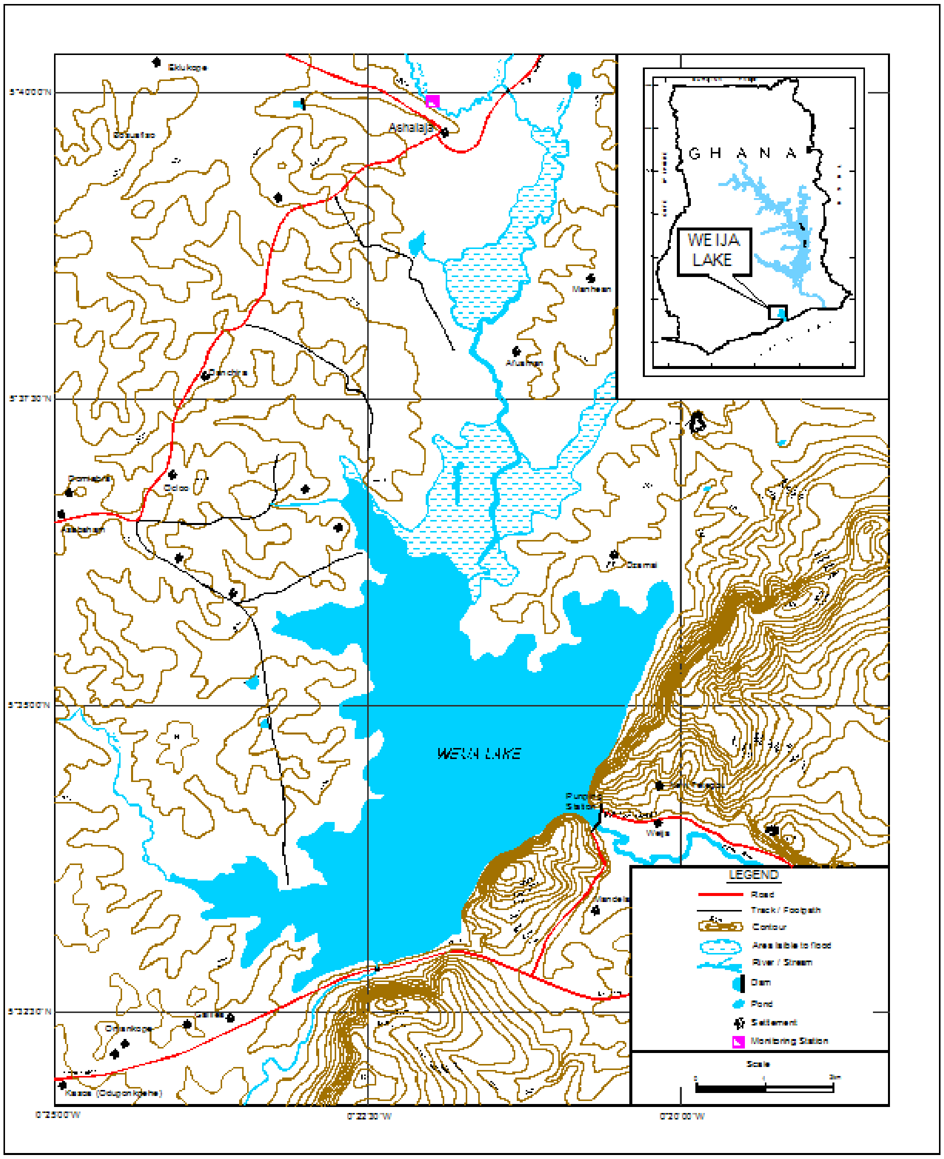


Fig. 1. Map of the study area showing the Weija reservoir and the monitoring station at Ashalaja (Source: Modified from Survey Department, 1999)

sediment laden runoff water from quarry sites.

Suspended sediment and river discharge monitoring

Weekly suspended sediment and river discharge measurements were monitored on the Densu river at Ashalaja. Due to lack of

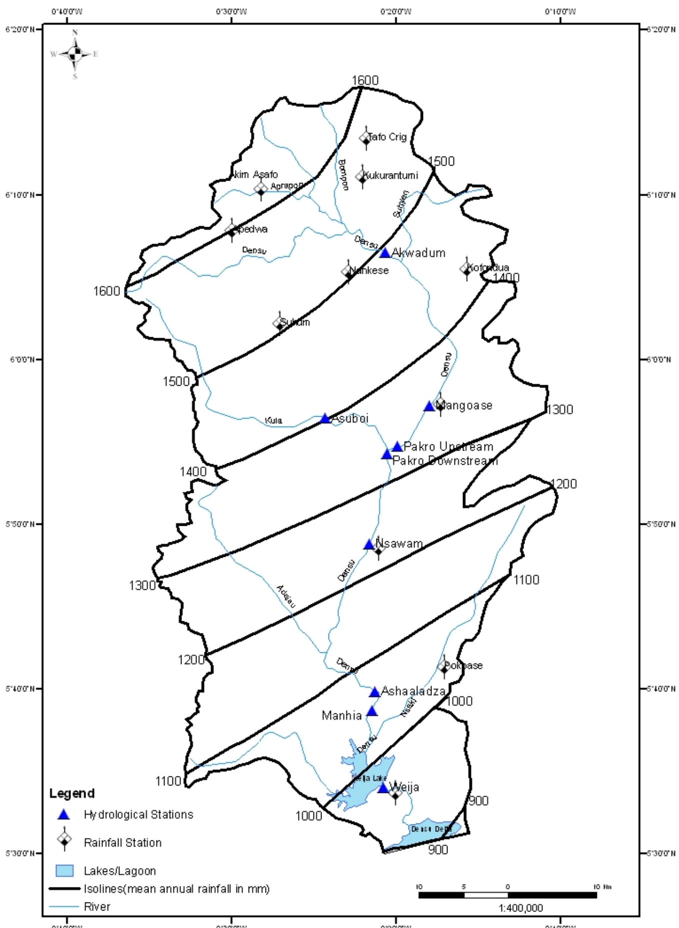


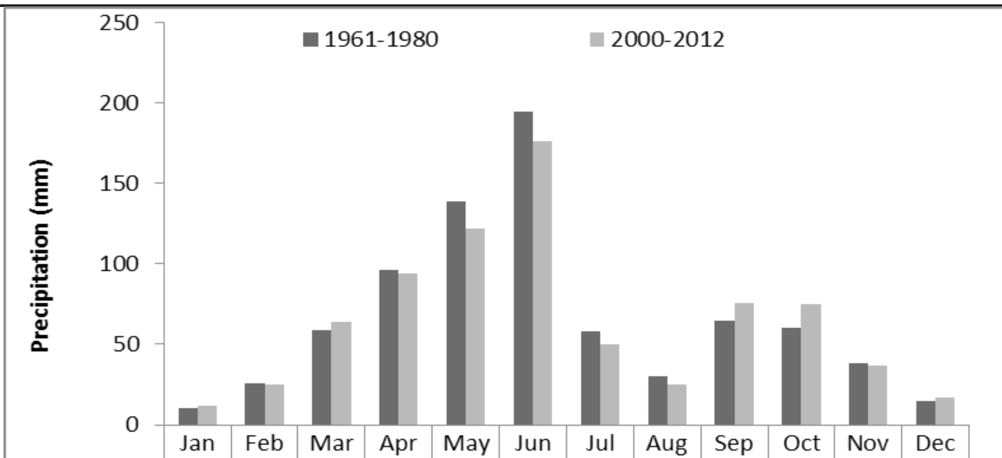
Fig. 2. Hydrological and isohyetal map of the Densu basin (Source: Modified from WRC, 2007)

sediment data, fresh sediment data had to be taken particularly close to the Weija reservoir. The Ashalaja station was selected for the sediment monitoring even though Manhia is a closer station to the Weija reservoir. Ashalaja station is easily accessible and had a bridge which allowed measurements to be taken during high flows when wading was impossible.

The river discharge measurements were taken with a Valeport current meter using both 2-point measurement and six-tenths-depth methods depending on the stage of the river. During high flows in the river channel, measurements were taken from the bridge using the current meter with suspenders and varying weights of Columbus C-type sounding weights. Wading rods were used with current meter during low stream flows. Mean discharges were subsequently computed using the mean flow velocity and cross-sectional area of the river channel.

Suspended sediment samples were taken from three sampling points on the river transect concurrently with river discharge measurements. The suspended sediment samples were collected using a depth-integrating sampler (USDH-48). Total suspended sediment concentrations were estimated to be the summation of the suspended sediment concentration determined from samples, and bed load concentration was assumed as 10 per cent of the suspended sediment concentration following Akrasi (2008).

Suspended sediments samples were also collected from the Weija reservoir at three section transects within the reservoir on 25th January 2013 when the reservoir received low flows from the rivers. The suspended sediment samples were taken near the dam



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1961-1980	10	26	59	96	139	195	58	30	65	60	38	15
2000-2012	12	25	64	94	122	176	50	25	76	75	37	17

Fig. 3. Mean monthly rainfall distribution at Weija for periods 1961 – 1980 and 2000 – 2012, showing seasonal variability.

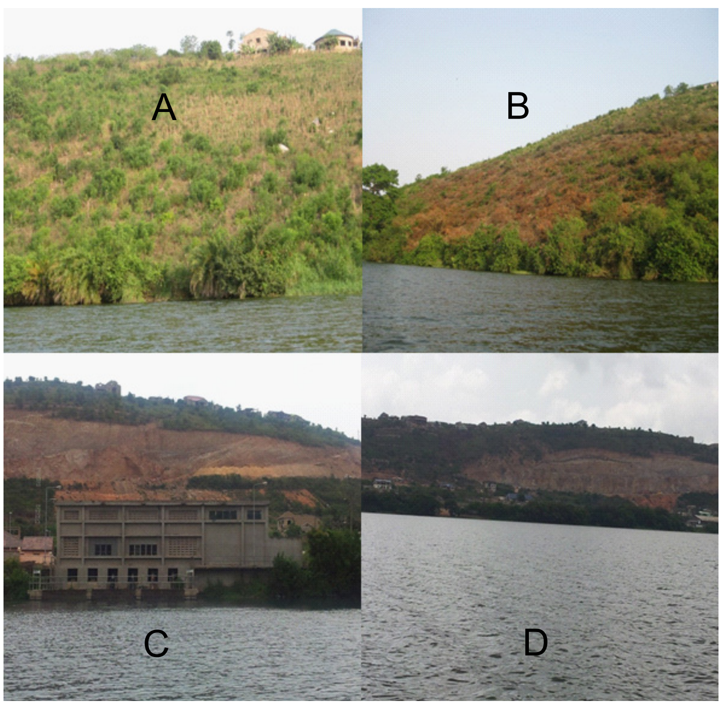


Fig. 4. A: Hills surrounding the Weija reservoir subjected to farming (stocks of maize interspersed with the vegetation); B: Hills sounding the Weija reservoir prepared for cultivation of cereals (brown patches) and C & D: Quarry sites overlooking the Weija reservoir

wall, in the middle and estuarine sections to the Densu, Nsaki and Gyei rivers (Fig. 4). Sediment deposits in the reservoir were obtained using the Ekman Bottom Grab Sampler to determine the particle size distribution of the bottom material.

The suspended sediment samples were analysed for sediment concentration at the sediment laboratory of the CSIR- Water Research Institute using oven dry protocol (Tilrem, 1979). Particle size distribution of the reservoir bottom material (deposited sediment) was determined using sieve analysis method following Lane *et al*. (1947).

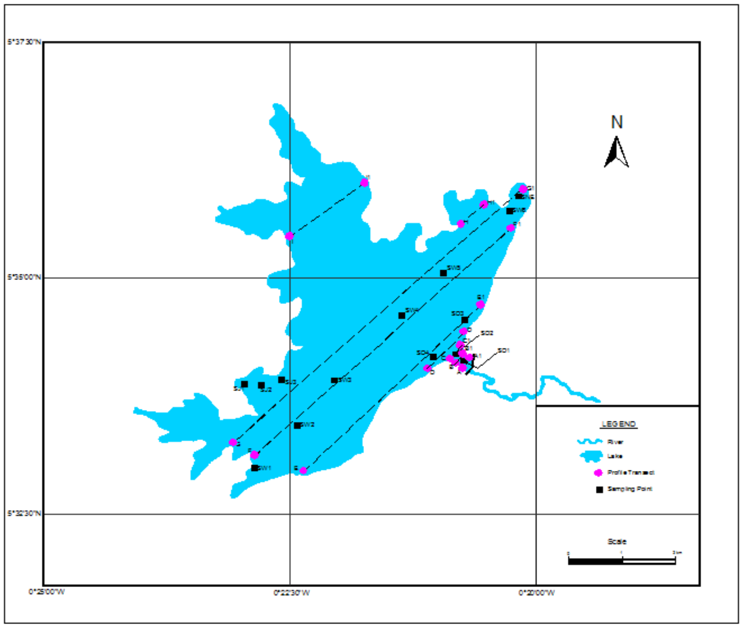


Fig. 5. Areal map of the Weija reservoir with profile transects sediment sampling points

Suspended sediment discharge and rating curve

The suspended sediment discharge from each measurement was derived as:

$$Q_s = 0.0864\, C_s\, Q_w \qquad (1)$$

where Q_s is suspended sediment discharge in t day^{-1}, Q_w is the river discharge in m^3 s^{-1} and C_s is the total suspended sediment concentration in mg l^{-1}. Weekly mean and annual mean sediment discharges were subsequently estimated from the daily mean suspended sediment discharge computed from (1).

A suspended sediment discharge rating curve developed for the Densu river at Ashalaja was represented by a power function equation in the form:

$$Q_s = aQ_w^{\ b} \qquad (2)$$

where Q_s is total suspended sediment discharge in t day^{-1}, Q_w is the river discharge (m^3 s^{-1}), and a and b are index of erosion severity and exponent (constants), respectively, obtained by log-log plot of (2). The rating curve was evaluated using a coefficient of determination (R^2) greater than 0.6 (Lima *et al*., 2005).

Results and discussion

Suspended sediment concentration

In general, the fluctuations in river discharge, and daily mean suspended sediment concentration were in response to rainfall (Fig. 5), thus, the time-series mimiked the seasonal rainfall pattern in the basin. There was a sharp increase and decrease of the daily mean suspended sediment concentration from the start of the rainy season (April to May), and subsequently towards the peak river discharge in June which corresponds to the peak rainfall month in the basin. The sharp increase and decrease of the daily mean suspended sediment concentration during the start of the rainy season, is likely due to the availability of sediments in parts of the basin where sand winning activities (mostly during the dry season) were prominent.

The daily mean suspended sediment concentration ranged from 10 mg l^{-1} to 281 mg l^{-1} with a mean of 47 mg l^{-1}. The highest daily mean suspended sediment concentration was recorded in May during the start of the rainy season. This may be due to the available sediments in parts of the basin and, therefore, during the start of rainy season, it becomes available for transportation.

Suspended sediment rating curve

The rating relationship fitted to the sediment load data for the Densu river at Ashalaja was found to be (Fig. 6):

$$Q_s = 2.9394Q_w^{1.0574} \quad (3)$$

where a = 2.9394 and b = 1.0574 with a significant ($\alpha = 0.05$) coefficient of determination (R^2) of 0.84. The coefficient of determination indicated the relationship was a good fit.

The b value is consistent with similar studies (Table 1) in the south-western and coastal river basin systems. Akrasi (2011) and Kusimi *et al*. (2014) had indicated that, the exponent value between 2 and 3 indicates that sediment load increases mostly with increases in river discharge or during high flow events. The b value of 1.0574 derived in the study suggested that, sediment transport in the basin was largely due to availability of sediment in the upper catchment of the monitoring point and not just due to high river discharges. Thus, suspended sediment discharge can be high over a wide range of river flow scenarios so far as there is availability of sediments in parts of the basin. Also, a value of 2.9394 (a > 1) indicated that parts of the basin was degraded. Akrasi (2011) reported that, a key feature of south-western and coastal rivers systems is that the basins respond to localised storms in generating sediment inputs to the river systems which are unrelated to the overall water discharge regimes. This means that sediments generated as a result of anthropogenic activity in the basin can be mobilised and transported via the Densu river into the Weija reservoir.

Suspended sediment yield

The daily mean suspended sediment discharge ranged from 0.11 to 74 t with a mean of 15 t. The estimated daily mean suspended

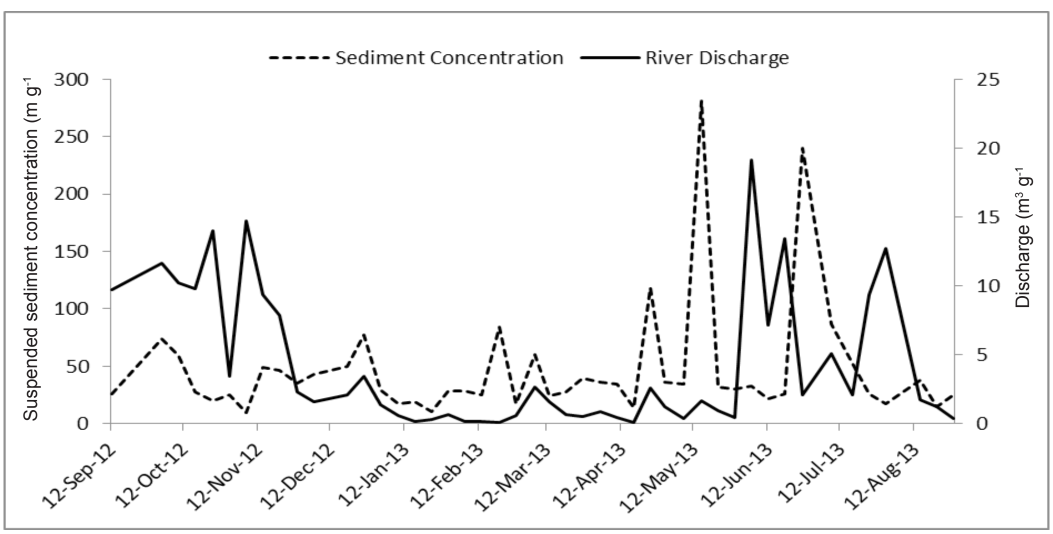


Fig. 6. Daily mean suspended sediment concentration at Ashalaja on sampling days

sediment discharges for the major and minor rainfall seasons were 21 t and 33 t, respectively, compared to 8 t during the dry season (low river discharge). This is consistent with other studies (Akrasi, 2008; Kusimi *et al*., 2014), where suspended sediment discharge increases during high river discharges (major and minor rainy seasons) compared to low river discharges (dry season). However, the highest sediment discharge was recorded during the minor rainfall season with a peak discharge of about 74 t recorded in October, confirming the availability of sediments for transport and also, partly to the higher rainfall amounts during the minor seasons in the latter decade.

The total annual suspended sediment yield and the annual specific suspended sediment yield were estimated as 5,375 t and 2 t km^2, respectively. The total annual suspended sediment yield and annual specific suspended sediment yield from the study were relatively low compared to mean annual and mean annual specific suspended sediment yield for other river basins in Ghana, particularly, the south-western basin where high anthropogenic activities such as illegal small scale mining (known as galamsey) were prominent (Table 1). The relatively low annual suspended sediment yield and annual specific suspended sediment yield were due to the IWRM interventions in the basin, since past studies in the Densu basin at Mangoase showed relatively higher values (Table 1). Thus, even though there has been a reduction in the total annual yield in the study, the sediment discharges into the reservoir were still a challenge to GWCL (Gandaa, verbal communication).

Reservoir suspended sediment concentration

The suspended sediment concentrations measured from the estuarine, middle and

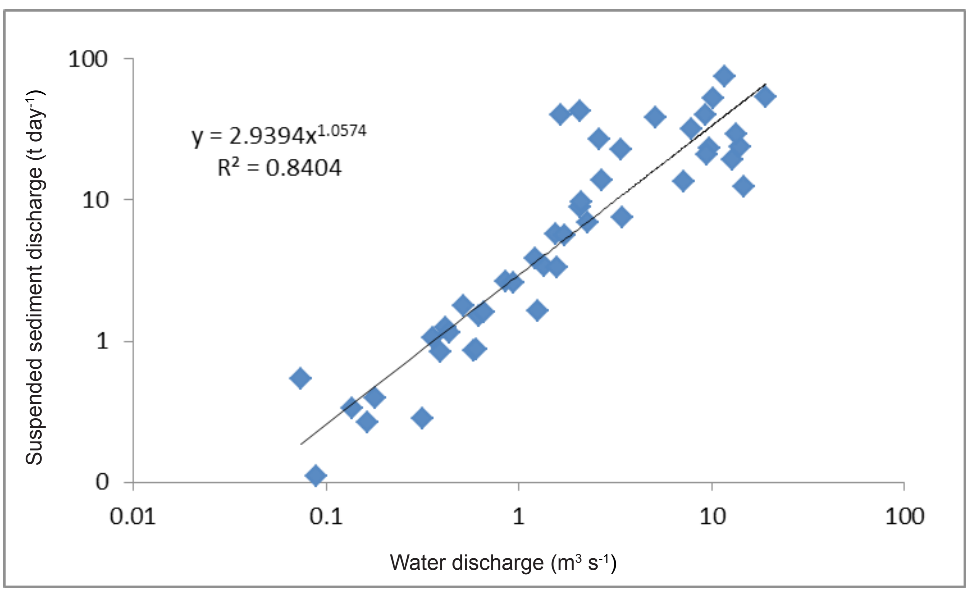


Fig. 7. Suspended sediment rating curve for the Densu river at Ashalaja

near-dam wall sections of the reservoir ranged from 11.3 to 40.7 mg l^{-1}, 8.0 to 28.1mg l^{-1} and 12.6 to 19.8 mg l^{-1}, respectively. The mean suspended sediment concentration for the estuarine, middle and near dam wall sections of the Reservoir were 24.6 mg l^{-1}, 16.1 mg/l and 15.0 mg l^{-1}, respectively. The mean suspended sediment concentrations in various sections of the reservoir were relatively high compared to raw water target quality of 5 mg l^{-1} (WRC, 2003). Suffice to say that the utility provider, GWCL spends a significant amount for treating water from the Weija reservoir (Gandaa, verbal communication).

Indications from the operators of the reservoir, GWCL, suggests that sediment from the cultivated hills around the reservoir and the quarry sites overlooking the reservoir (Fig. 4) may be a concern. From field observations, the quarry sites did not have any water retention or run-off control structures to prevent high sediment laden run-off water from the sites. It is likely the sediments transported from these sites make up significant proportion of the total sediment inflow into the reservoir, particularly, during rain storms.

Conclusion and recommendations

Assessment of sediment transport into the Weija reservoir was undertaken to provide useful information for assessing the effectiveness of future IWRM interventions. The study found that, the total annual yield and annual specific yield for the Densu basin at Ashalaja were lower compared to those obtained from other river basins of Ghana including past studies in the Densu basin at Mangoase which is upstream of Weija. The IWRM interventions being implemented

TABLE 1

Mean annual suspended sediment yield and mean annual specific suspended sediment yield major river basins in south-western, coastal and Volta river basin systems

River	Station	Catchment area (km^2)	Mean annual suspended yield ($t\ yr^{-1}$)	Mean annual specific suspended sediment yield ($t\ km^{-2}\ yr^{-1}$)	Slope of log-transform rating curve, b
Densu*	Ashalaja	2,600	5,375	2.00	1.057
Densu	Mangoase	817	6,146	2.49	1.386
Bia	Dadieso	6,110	11,960	1.96	1.136
Tano	Sefwi-Wiawso	88,030	1,546	0.19	0.854
Ankobra	Prestea	4,268	18,723	4.39	1.441
Butre	Ewusiejoe	365	2,988	8.19	1.415
Pra	Daboase	22,818	189,037	8.28	1.52
Ochi-Amisa	Mankessim	1,217	4,654	3.71	1.164
Ochi-Nakwa	Ekotsi	1,383	5,883	4.25	0.886
Black Volta	Bamboi	132,557	5,295,055	39.95	1.109
Black Volta	Lawra	92,877	625,610	6.74	1.253
White Volta	-	106,742	4,000,000	32.56	-
Oti	-	75,110	5,000,000	63.26	-

* Mean specific suspended sediment yield from the study (Source: Akrasi, 2008; Akrasi, 2011; Ofori *et al*., 2011)

by the Water Resources Commission are reducing the amount of sediment available for transport via the Densu river. However, suspended sediment yields entering the reservoir present a challenge to GWCL.

A suspended sediment yield rating curve established for the Densu river basin at Ashalaja gauging station is a good fit. The parameters of the curve indicate land degradation in parts of the basin and sediment transport in the basin is largely due to availability of sediment. The rating curve established in the study can provide useful information for future studies by comparing with other annual yields to determine the range of yields for a typical wet/dry hydrological year as well as, average yield over a period which ultimately, can be used to assess the effectiveness of the IWRM interventions being implemented in the basin.

Suspended sediment concentration estimated in sections of the reservoir was, however, relatively high compared to target water quality range. Field observations and indications from the water utility company and operator of the reservoir, GWCL, suggests that sediment laden runoff from the hilly areas surrounding the reservoir, and the quarry sites overlooking the reservoir may be a concern and likely be a significant proportion of the total sediment inflow into the reservoir.

It is, therefore, recommended that the IWRM interventions being implemented in the basin be intensified. The developed National Buffer Zone Policy should be fully implemented in the basin without further delay, to help reduce the transport of sediment into the river system from the upper catchment of the basin and directly into the reservoir. The implementation of the IWRM plans for the basin should include those activities planned for public education with emphasis on water conservation and environmental integrity of the basin. Water spreading structures and water retention structures should be considered and constructed at the quarry sites to prevent the sediment laden runoff water being transported into the reservoir.

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