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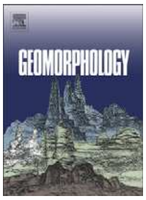

Estimating the fluvial sediment input to the coastal sediment budget: A case study of Ghana

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ABSTRACT

Knowledge of fluvial sediment supply to the coastal sediment budget is important for the assessment of the impacts on coastal stability. Such knowledge is valuable for designing coastal engineering schemes and the development of shoreline management planning policies. It also facilitates understanding of the connection between rivers in the hinterland and adjoining coastal systems. Ghana's coast has many fluvial sediment sources and this paper provides the first quantitative assessments of their contributions to the coastal sediment budget. The methods use largely existing data and attempt to cover all of Ghana's significant coastal rivers. Initially work was hindered by insufficient direct measured data. However, the problem was overcome by the application of a regression approach, which provides an estimated sediment yield for non-gauged rivers based on data from gauged rivers with similar characteristics. The regression approach was effective because a regional coherence in behaviour was determined between those rivers, where direct measured data were available. The results of the assessment revealed that Ghana's coast is dissected by many south-draining rivers, stream and lagoons. These rivers, streams and lagoons supply significant amounts of sediment to coastal lowlands and therefore contribute importantly to beaches. Anthropogenic impoundment of fluvial sediment, especially the Akosombo dam on the Volta River, has reduced the total fluvial sediment input to the coast from about 71×10^6 m^3/a before 1964 (pre-Akosombo dam) to about 7×10^6 m^3/a at present (post-Akosombo dam). This sharp reduction threatened the stability of the east coast and prompted an expensive ($83 million) defence scheme to be implemented to protect 8.4 km-long coastline at Keta. Sections of Ghana's coast are closely connected to the hinterland through the fluvial sediment input from local rivers. Therefore, development in the hinterland that alters the fluvial sediment input from those local rivers could have significant effects on the coast. There is the need, therefore, to ensure that catchment management plans and coastal management plans are integrated or interconnected.

1. Introduction

The coastal sediment budget analysis provides a valuable framework for bringing together the necessary information for the understanding and interpretation of sediment input, transfer, storage and output of a given coast (Bray et al., 1995; Cooper, 1997; French, 2001; Nelson and Booth, 2002; Finkl, 2004). Development of a coastal sediment budget offers a means of identifying the links between coastal sediment sources and storages or sinks. Coastal sediment budget calculation is undertaken within a defined littoral cell (Bowen and Inman, 1966; Komar, 1996; Sanderson and Eliot, 1999; Eittreim et al., 2002). A conceptual model is prepared identifying the key elements (inputs, stores, sinks, outputs) and the transfers between them. The elements and transfers are then quantified and the results assembled to formulate the budget (Eittreim et al., 2002; Park and Wells, 2005; Cooper and Pethick, 2005; Rosati, 2005). The premise behind the concept of a coastal sediment budget is relatively simple. If more sediment is transported *into* a sediment cell than sediment transported *out* of the same sediment cell, shoreline accretion occurs. Conversely, if more sediment is transported out of a sediment cell than is transported *into*, shoreline erosion occurs. Balancing the inflow and outflow of sediment for a given littoral cell is important to maintaining stable beaches. This knowledge gives a strong understanding of the past, present and future shoreline change which also provides significant information for coastal management.

Despite the obvious value of the coastal sediment budget, it remains difficult to establish in practice (Eittreim et al., 2002; Townend and Whitehead, 2003). This is largely because all key components within the budget need to be identified, understood and quantified if the overall budget is to be reliable. Fluvial sediment discharge to the coastal environment is an important component (input) of many coastal sediment budgets (Komar 1996; Milliman and Syvitski, 1992; Syvitski, and Morehead, 1999; Willis and Griggs, 2003; Syvitski and Milliman, 2007). Knowledge of the quantity and characteristics of sediment input from fluvial sources is therefore important for management,

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development and conservation of coastal resources (Bray et al., 1995; Limber et al., 2008). Understanding of the long-term fluvial sediment loads and their characteristics is equally important in the design and management of water resources such as dams, canals, bridges, and water treatment plants (Vörösmarty et al., 2003; Ayibotele and Tuffour-Darko, 1979).

In Ghana, most fluvial sediment studies in the 1960s were influenced by water resources development projects such as the Volta hydro-electric dam and water treatment plants such as Densu, Kpone, Owabi and others around the country, which provide potable drinking water to many communities. The period between 1974 and 1996 saw a huge change from project-led fluvial sediment studies to more progressive research-based studies. The change was influenced by the benefits derived from fluvial data gathered in the 1960s. The Water Resources Research Institutes (WRRI) designed and implemented several systematic sediment sampling programmes which covered almost all the major river basins of the country. The programme which aimed at gathering fluvial sediment data to facilitate faster delivery of future water development projects generated discharge and sediment concentration data for most of the major rivers in Ghana. Despite the success of the WRRI programme, there is still a lack of data on the small rivers, streams and numerous coastal lagoons that receive discharge from rivers and streams. Furthermore, no previous studies had assessed in detail the extent to which fluvial sources contribute to the coastal sediment budget in Ghana (Collins and Evans, 1986).

It is important to develop knowledge on the quantity of fluvial sediment supply to the coastal sediment budget so as to identify the impacts of fluvial sediment on coastal stability (Phillips, 1991; Boateng, 2009). Such knowledge is valuable for designing coastal engineering schemes and the development of shoreline management planning policies. It also facilitates understanding of the connection between rivers in the hinterland and the coast. Ghana has many fluvial sediment supply sources but very little is known about how much sediment they contribute to the coastal budget.

Ly (1980) identified that coastal recession east of the Volta estuary (down-drift) doubled between 1964 and 1975 due to the Akosombo dam built on the Volta River, which intercepted and reduced significantly fluvial sediment yield from the river. In fact, the situation resulted in a rapid recession and losses of the shoreline and the settlements down-drift (between Keta and Hlove) until 2002 when a major sea defence project was completed (Ellicott Dredges, 2000). Similar observations have been made by many authors elsewhere regarding the impacts of dams on fluvial sediment discharge as a result of the trapping effects (Phillips et al., 2004; Phillips and Slattery, 2006; Torab and Azab, 2007; Burroughs et al., 2009). Hydro-electric and water projects are still being developed in Ghana (Kufuor, 2007). These projects could interfere with fluvial sediment loads with poorly understood effects downstream and at the coast.

This paper provides holistic assessment of the fluvial sediment input to Ghana's coast by means of analysing largely existing sediment discharge data on coastal rivers. It identifies the magnitude of fluvial sediment input to the coastal budget of Ghana and evaluates the possible effects of future dams on the coast.

2. The study area

The land area of Ghana is drained by many rivers and streams. Akrasi and Ayibotele (1984) divided Ghana into two distinct drainage areas; the Volta and the south-western basins (Fig. 1). The Volta and the south-western basins account for 75% and 25% of the land area of Ghana, respectively, and are separated by Kwahu plateau, which runs in a north-westerly direction from Koforidua to Wenchi at elevations between 300 and 800 m. The topography of the south-western drainage basin is generally undulating and slopes gently southwards at elevations ranging between 150 and 300 m above sea level. The coastal areas are generally flat with the exception of a few isolated, elevated inselbergs and the Volta dam which isolates its drainage basins.

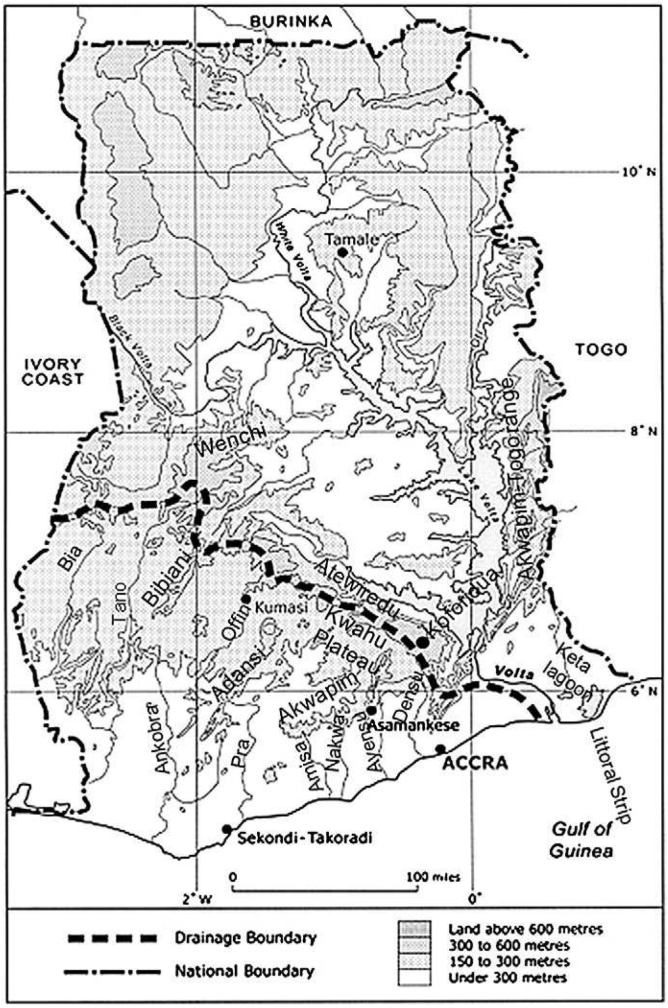


Fig. 1. The physical map of Ghana showing the River Volta and south-western basins. After the Survey of Ghana (1969).

The watershed which separates the two drainage basins in Ghana comprises four major mountain ranges (Akwapim, Atewiredu, Adansi and Bibiani) that have north-west and south-west trends. All the major rivers (Bia, Tano, Ankobra, Pra, Offin, Ayensu, Nakwa and Densu) in the south-western drainage basin originate in the mountain range between Koforidua and Wenchi and flow south-west into the sea, often through coastal lagoons (Fig. 1). The Volta basin is bordered by the Akwapim-Togo range. This south-eastern mountain range rises to a peak of 870 m (Ayibotele and Tuffour-Darko, 1979). The littoral strip that fringes Volta delta and the Keta lagoon is the lowest area (0–1 m) above sea level in Ghana.

The geology of Ghana ranges from the old Precambrian formations known locally as the Birrimian and the Tarkwaian to the recent unconsolidated Quaternary formation (Volta delta and coastal areas). The geology determines the resistance to erosional processes. Soft geological formations such as the highly permeable recent materials in the south-east and the shale, locally called Sekondian and Accraian, are less resistant than stronger geological formations like the granite complex and the Precambrian formations such as the Birrimian and Tarkwaian (Fig. 2).

The maximum and minimum sediment discharge rates of rivers are mostly linked to the rainfall regime of a country (Peel, et al., 2004). The average annual rainfall pattern in Ghana is shown in Fig. 3. The rainfall increases from March and reaches a maximum in June and a second, lower maximum in October and then decreases to January. Thus, the

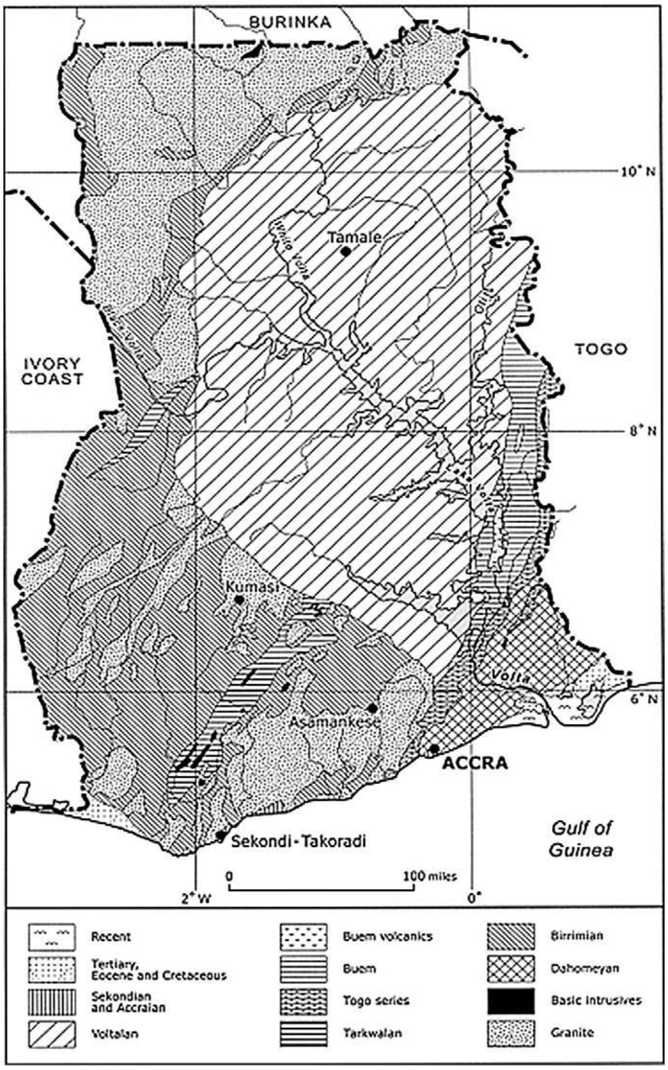
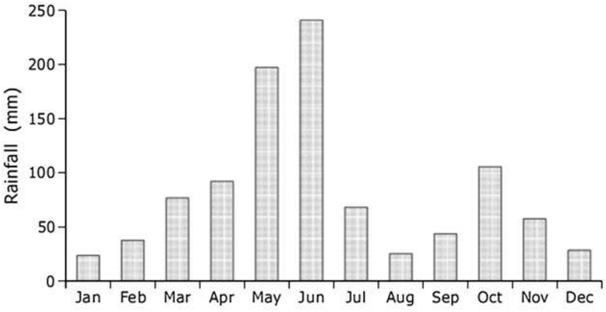


Fig. 2. The geology of Ghana.
Source: Boateng (1970).

main wet season months are May–June and October–November and the dry seasons are December–February and August–September. Most of the rivers transport eroded soil materials from their catchment areas and discharge them either to the inland reservoirs (behind dams) or ultimately to the coast directly and some through coastal lagoons. Many south-draining small rivers and streams empty into coastal lagoons that are either daily or seasonally sealed by barrier beaches. The daily sealed lagoon inlets are controlled by daily tidal range. The seasonally sealed lagoon inlets on the other hand are influenced by constructive wave action which builds the barrier across the inlets and seasonal storms from seaward or flash floods from landward which breach the barrier. On such occasions, rapid tidal flows that empty the lagoon are ebb flows, which are capable of flushing out much of the accumulated sediment. The neap and spring tidal range in Ghana is between 0.58 and 1.28 m (Allersma and Tilmans, 1993; Wellens-Mensah et al., 2002), which has a significant influence within tidal inlets. However, the rapid tidal flows and extreme flood events are influenced by upwelling and storm surges associated with onshore movement of rain-bearing south-west monsoon winds, which increases water levels to about 10 m and causes heavy rainfall between May and October (Wellens-Mensah et al., 2002).



Sources: After Armah and Amlalo (1998), Allersma and Tilman (1993)

Fig. 3. Average monthly rainfalls in Ghana.
After Armah and Amlalo (1998) and Allersma and Tilmans (1993).

3. Materials and methods

Sediment loads from rivers are very difficult to estimate in many instances (Amisigo and Akrasi, 1997). This is due to the high cost involved in gathering necessary measurements on daily or even hourly sediment concentration and bed-load for a reasonable period of time for accurate sediment yield estimation. As a result of this difficulty many authors in the past have used varied methodologies to estimate sediment yield of rivers that have no direct measured data (Miller, 1951; Schumm, 1977; Walling, 1977; Milliman and Meade, 1983; Milliman et al., 1999; Akrasi, 2005; Syvitski and Milliman, 2007). These include the erosion rate method, catchment-based method, rating curve method and regression method. The regression approach was adopted for the estimation of fluvial sediment yields in this study because it most effectively applies specific measured regional data where this is available. The approach has been used in many fluvial studies including Milliman et al. (1999), Mimikou (1982), Akrasi (2005), Taylor et al. (2006) and Ali and De Boer (2007).

Fluvial discharge and sediment data from the 1960s project-led studies and the well programmed WRRI studies between 1979 and 1993 were collated. The two datasets together offered a significant amount of data on rivers in Ghana which makes it possible for sediment discharge regression equations to be developed. The data were entered into statistical software (Minitab) which was used to generate the regression equations which were then used to estimate sediment yield from unmeasured coastal rivers.

Sediment loads of rivers are influenced by factors such as basin area, topography, geology and the climatic conditions of the local area (Jansson, 1988; Allersma and Tilmans, 1993; Milliman et al., 1999). The effects of these factors on sediment load vary in time and in space. In most cases, several of these factors may control sediment load of rivers in a given area (Walling et al., 2006; Ali and De Boer, 2007). This implies that local or regional rivers often show similar characteristics; hence reliable estimates could be obtained from a regression equation that is derived from data on regional rivers that have broadly similar characteristics.

Sediment discharge data obtained from two studies published by the WRRI (Ayibotele and Tuffour-Darko, 1979; Amisigo and Akrasi, 1997) were used to derive regression equations for the estimation of fluvial sediment yield in this study. The sediment yield estimates in the two studies were based on continuous sampling of southern rivers for 12 years (Amisigo and Akrasi, 1997) and instantaneous sampling of south-western rivers for an average period of 3 years (Ayibotele and Tuffour-Darko, 1979). The sampling procedure at the gauging stations (Fig. 4), laboratory analysis and the method used to compute the sediment yield of the sampled rivers have been well explained in Ayibotele and Tuffour-Darko (1979) and Amisigo and Akrasi (1997).

3.1. A review of previous fluvial sediment yield approaches in Ghana

The sediment load of a river comprises suspended sediment load and bed load (Jansson, 1988; Walling, 1984; Milliman et al., 1999). It

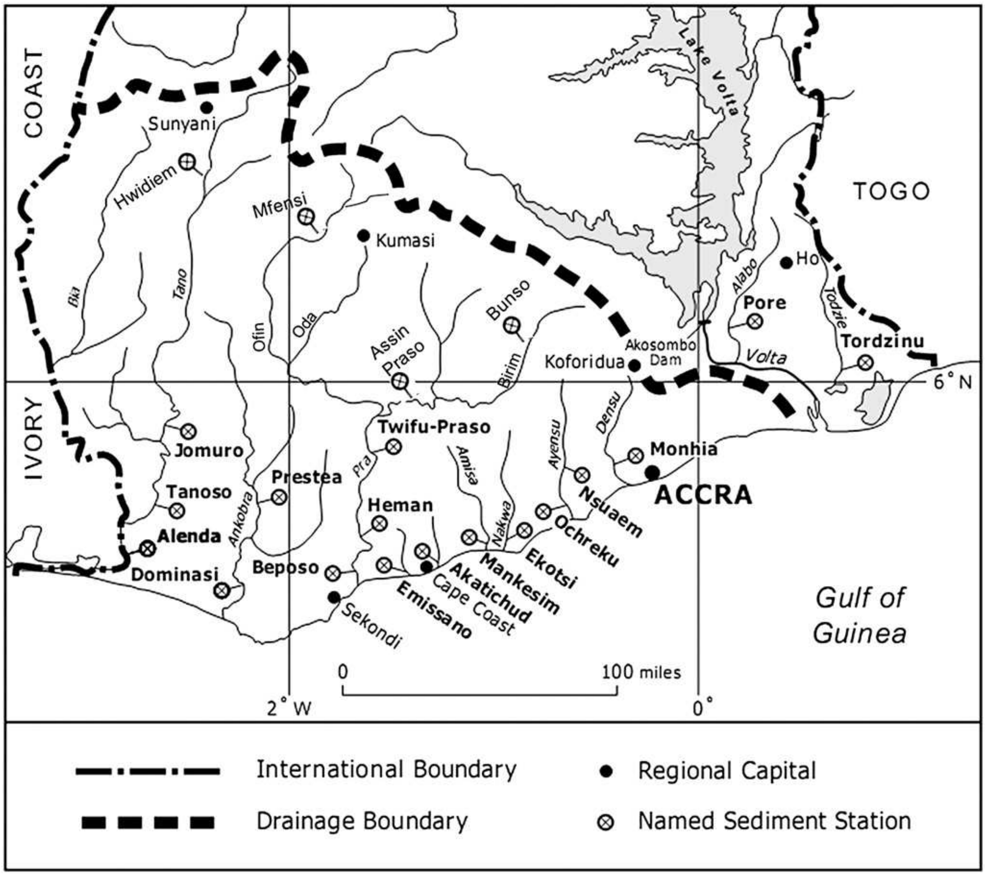


Fig. 4. Gauging stations of the southern and south-western rivers sampled.

is worth nothing that the sediment data obtained from Ayibotele and Tuffour-Darko (1979) covered both suspended sediment discharge and bed load of the rivers studied. Their laboratory analysis was based on the "bottom withdrawal method" which uses an analytical approach for the determination of size gradation from dispersal sedimentation data. Following the laboratory analysis, suspended sediment yields and bed load were computed using the two equations below.

Suspended sediment discharge:

$$Q_{si} = Q_{wi} \times C_s \times K_s \tag{1}$$

where

Q_{si}	Instantaneous suspended-sediment discharge in metric tonnes/day.
Q_{wi}	Instantaneous water discharge in m^3/s.
C_s	Concentration of suspended sediment sample in mg/l.
K_s	A factor of conversion to metric tonnes/day.

Bed load:

$$S = 6.5d(\Delta g)^{1/2}\left(V^{3/2} \times \left(K_s^i\right)^1 \Big/_4{}^{/}96\Delta d – 0.047\right)^{3/2} \tag{2}$$

where

S	Bed load transport in m^3/unit width/s.
d	Mean diameter of particles in sample.
V	Velocity of the river in metres per second.
K_s	Sand roughness coefficient = d_{90} of bottom material.
i	Slope of the river bed.
g	Acceleration due to gravity = 9.81 m/s^2.
Δ	Relative density of sediment = 1.68 kg/m^3

The study conducted by Amisigo and Akrasi (1997) on the other hand, used the flow duration–sediment rating curve method (Miller, 1951; Piest, 1964) for the computation of sediment yield. They sampled only suspended sediment load of the south-western river basins (Pra, Ankobra, Tano, Bia and their tributaries) and assumed 10% of suspended sediment as the bed load, citing Walling (1984). However, their studies covered only a small proportion of the total rivers and streams discharging sediment at the coast for which input data were required. Below is the suspended sediment discharge rating equation derived and applied by Amisigo and Akrasi (1997).

$$Q_s = kQ_w^n \tag{3}$$

where

Q_w	average stream flow for a duration increment, m^3/s
Q_s	corresponding suspended sediment discharge, metric tonnes/day
k, n	constants.

3.2. An assessment of regional and seasonal variation in discharge

In order to identify the regional and seasonal variation of sediment load of rivers in Ghana, a regional and seasonal best-fit regression analysis was used to establish the scale of variations of measured suspended sediment and bed load, respectively, against discharge, based on: (1) rivers classified by region and topography (Figs. 5, 6) and (2) by climatic seasons (Figs. 7, 8). The trend lines in Figs. 5, 6, 7 and 8 were derived from measured suspended and bed load sediment transport of seven major coastal rivers of Ghana for an average period of 3 years (Ayibotele and Tuffour-Darko, 1979). The data points represent the mean

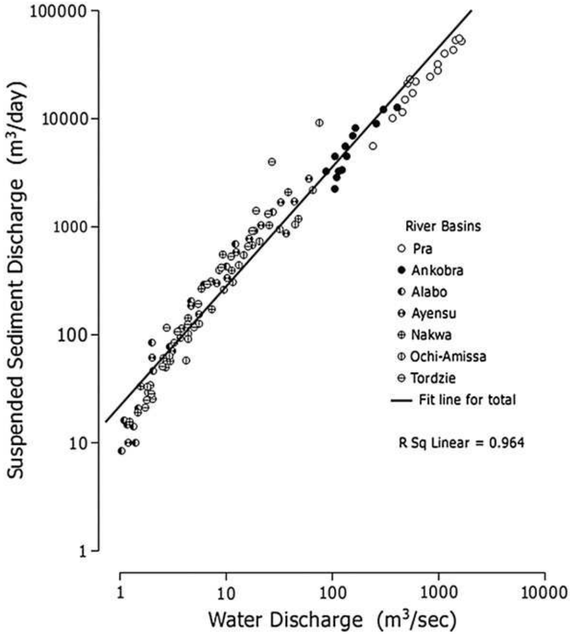


Fig. 5. Regional suspended sediment transport curve of the major coastal rivers in Ghana.

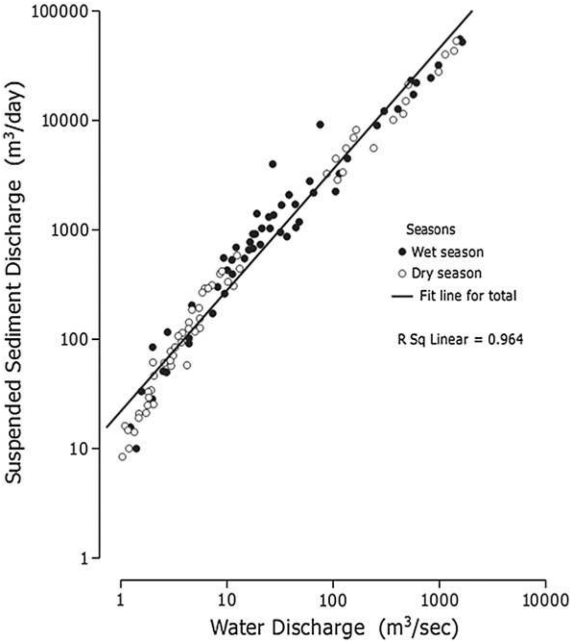


Fig. 7. Seasonal suspended sediment transport curves of the major coastal rivers in Ghana.

instantaneous sampling over the period. The mean annual discharge results indicated that topography and climatic seasons have little influence on suspended and bed load sediment yield of rivers in Ghana (Figs. 5, 6, 7, 8). Furthermore, both suspended and bed load sediment transport showed a strong regional coherence, indicated by the strong correlations in each instances. The coefficients of determination (r^2) for the relationships were 0.96 and 0.87, respectively.

The reason for this strong correlation might be the fact that the data used for the assessment covered a well defined relatively homogeneous area in southern Ghana that has less varied east to west relief and climate than the north (Benneh and Dickson, 1988).

The identification of a strong regional and seasonal coherence of sediment yield conforms to the outcomes of previous studies, which identify strong dependence of sediment load on catchment area of rivers of West Africa (Milliman and Meade, 1983; Walling, 1984; Milliman and Syvitski, 1992). This provided a good opportunity and strong justification to use a regression model of sediment yield versus catchment area to predict a reliable sediment yield from those coastal rivers which have no measured sediment data.

3.3. Deducing the regression equations and estimation of the fluvial sediment yield

First, the relationship between catchment area and discharge was tested, using the suspended sediment discharge data of 11 stations (Table 1) sampled for an average period of 12 years (Amisigo and Akrasi, 1997, WRRI). The suspended sediment yields (tonnes/year) were plotted against the catchment area (km^2) of all the 11 stations. Then both linear and quadratic regression relationship were derived by plotting the best fitted curves for the two parameters (Fig. 9). The results were very positive but the quadratic regression relation was applied because it provided a better exponential that the linear one. The correlation coefficient (r^2) between sediment yield and catchments for the quadratic

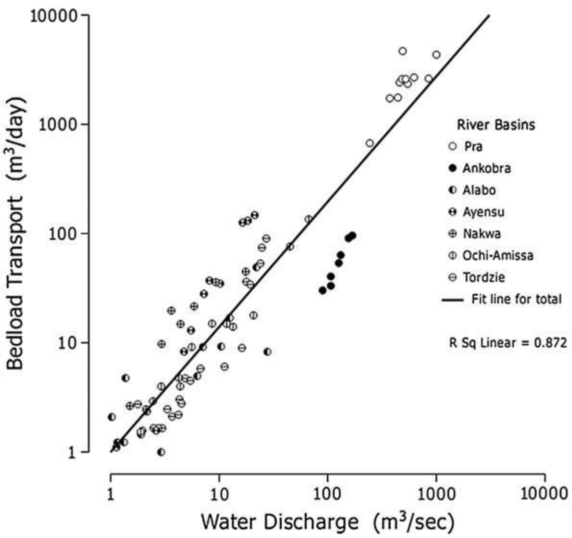


Fig. 6. Regional bed load transport curve of the major coastal rivers in Ghana.

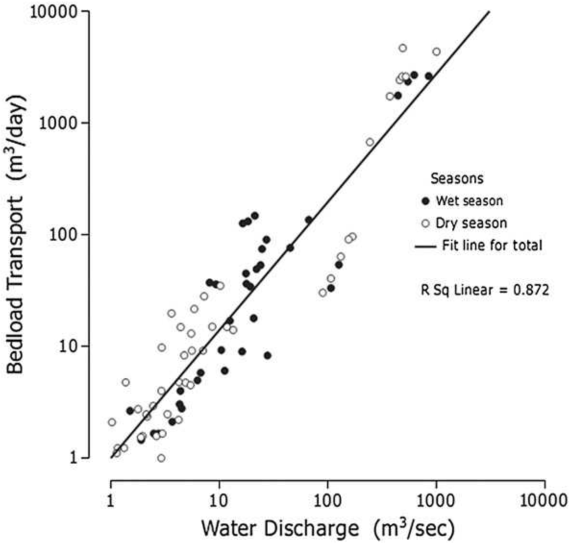


Fig. 8. Seasonal bed load sediment transport curve of the major coastal rivers in Ghana.

Table 1
Summary of measured suspended sediment yield, catchment and stations.

River	Station	Catchment area (km^2)	Suspended sediment yield (tonnes/year)
Birim	Bunso	150	1387
Anum	Konongo	681	1758
Bonsa	Bonsaso	1194	8614
Oda	Anwia Nkwanta	1303	3248.5
Ofin	Mfensi	1515	3905.5
Tano	Hwidiem	2844	2518.5
Ankobra	Prestea	4268	19,564
Pra	Assin Praso	9793	32,083.5
Tano	Jomuro	10,414	17,629.5
Pra	Twifo praso	20,767	56,975.5
Pra	Beposo	22,818	79,205

relation was 0.98 (Eq. (4)). The average catchment used to establish this quadratic relation was above 5000 km^2, but the catchment area of the coastal rivers ranges from as low as 3 km^2 to 394,100 km^2. It was obvious from the range of catchments that a different regression equation could be required for the small catchments below 5000 km^2 since small catchments are often recorded as having proportionally large yields (Milliman and Syvitski, 1992). Using the same data source, seven stations with catchments below 4500 km^2 were used to establish a regression relation for small catchments. This time a linear relation (Eq. (5)) was established rather than a quadratic relation because it offered the best fit with a correlation coefficient (r^2) of 0.61 between the two parameters (Fig. 9). The regression equations obtained for both large catchments and small catchments are Eqs. (4) and (5), respectively. The lower r^2 in Eq. (5) implies that small catchments are much more variable than the larger ones, as has been found elsewhere (e.g. Knighton, 1998).

$$\text{Suspended Sediment Yield (t/year)} = 20722 - 1.127 \times a + 0.001422 \times a^2 \ldots \left(r^2 = 0.98\right) \tag{4}$$

$$\text{Suspended Sediment Yield (t/year)} = -108 + 15.80 \times a \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \left(r^2 = 0.61\right) \tag{5}$$

where a = catchment area (km^2) and t = tonnes.

The results (tonnes/year) in Eqs. (4) and (5) were converted into cubic metres/year using a conversion scale of 1.602 tonnes to 1.0 m^3. This conversion was done to ensure that the same unit of measurement was used. Eq. (4) was used to predict suspended sediment yield of all rivers with catchment areas of 5000 km^2 and above, and Eq. (5) for rivers with catchment areas below 5000 km^2. Although, Ghana has substantial sediment data on rivers in the country, data on coastal rivulets and lagoons with catchment areas between 3 and 200 km^2 are very limited so it was not possible to improve Eq. (5). However, these were the most frequent catchment sizes in the coastal zone. There was the need, therefore, to use the available data to get the best and reliable estimates for these small rivulets and lagoons, hence the derivation and use of Eq. (5).

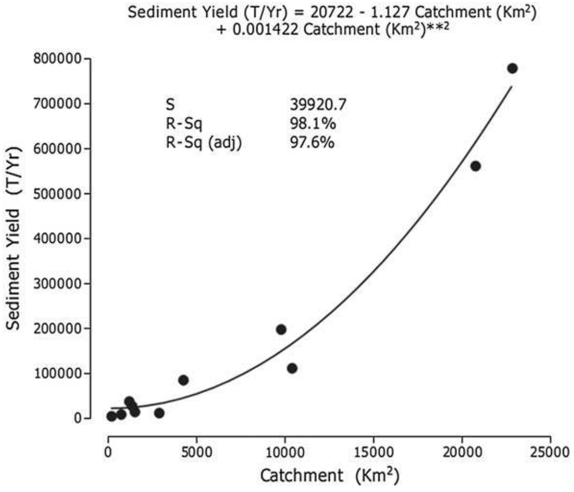


Fig. 9. Relationship between annual sediment yield and catchment areas of large rivers in Ghana.

The 11 gauging stations that provided sediment yield data used to establish Eqs. (4) and (5) did not have measured bed load of the sampled rivers, so the equations are only for the suspended sediment yield. The stations' bed loads were assumed to be 10% of suspended sediment load. This phenomenon is not peculiar to Ghana's fluvial data but seems to be a common practice in fluvial sediment studies as most studies tend to ignore bed load or use the 10% assumption (Walling, 1984; Vörösmarty et al., 2003; Willis and Griggs, 2003; Phillips et al., 2004; Akrasi, 2005; Phillips and Slattery, 2006).

In most sediment yield studies in the literature, only the suspended part of the total sediment load of rivers are considered, because bed load is seldom measured or estimated (Jansson, 1988). The assumption that 10% of suspended sediment yield represents the bed load has been rebuffed by some authors based on empirical evidence, which suggests that bed load could range between 4% and 60% of suspended sediment (Jansson, 1988; Nouh, 1988; Salemi et al., 2008). Furthermore, bed load sediments are of greatest value to beaches since they are mostly coarser, and thus stay in the coastal environment, than suspended sediment which is relatively fine and may be carried away in suspension from the beach by waves and tidal currents. Undoubtedly, bed loads are very important to the coastal sediment budget. Consequently, an effort was made to obtain a reasonable set of bed load estimates for the large rivers. One of the WRRI studies conducted between 1974 and 1976 (3 years) measured bed load at eight different gauging stations on some of the large rivers (catchment areas >2000 km^2) in Southern Ghana (Ayibotele and Tuffour-Darko, 1979).

The bed load data were only related to mean annual water discharge in those studies; hence a regression equation that could be derived from the data could be used to predict bed load more widely only if data on mean annual water discharge of local rivers are given. This poses a problem because none of the parameters (catchment area and suspended sediment yield) that were used to derive Eqs. (4) and (5) could be used in the estimation of bed load. However, it was identified that the data that were used to derive Eqs. (4) and (5) have the mean annual water discharge of the sampled rivers. This provided an opportunity to use a "bi-model" approach (Milliman and Syvitski, 1992) to predict bed load of the large rivers. Using the data that were used to derive Eqs. (4) and (5), mean annual water discharges were plotted against catchment areas (Fig. 11) and a linear regression (Eq. (6)) was obtained from the best-fitted line of the relation. Then the mean annual water discharge estimates obtained from Eq. (6) were plotted against mean bed load per year (Fig. 12) and a linear regression (Eq. (7)) was derived and used to estimate the bed load of large rivers. This plot was done because previous plots (Figs. 6, 8) focus on region and season rather than catchment.

Fig. 9 shows an excellent curve relationship between suspended sediment yield and catchment areas of large rivers. The relation has an exponential coefficient (r^2) of 0.98. Fig. 10 shows the linear relationship between suspended sediment yield and catchment areas of small rivers. The small rivers relatively have a lesser correlation, which is indicated by a lower exponential coefficient (r^2) of 0.61. Both Figs. 11 and 12 show excellent linear relationships between the parameters under consideration. The plot of Mean Annual Discharge against Catchment has an r^2 of 0.93 and the plot of Mean

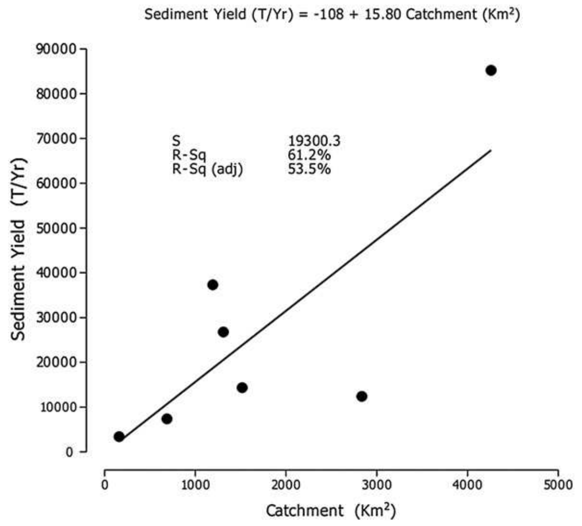


Fig. 10. Relationship between annual sediment yield and catchment areas of small rivers in Ghana.

Bed Load against Mean Annual Discharge has an r^2 of 0.86. These indicate a strong correlation between the parameters.

$$\text{Mean Annual Water Discharge } \mathrm{m}^3/\mathrm{s} = -422 + 3.050 \times a \ldots\ldots \left(r^2 = 0.93\right) \tag{6}$$

$$\text{Mean Bed Load}\left(\mathrm{m}^3/\mathrm{a}\right) = -520.6 + 1.961 \times d\left(\mathrm{m}^3/\mathrm{s}\right) \ldots\ldots\ldots\ldots\,.. \left(r^2 = 0.86\right) \tag{7}$$

where a = Catchment and d = Mean annual water discharge.

It is worth noting that the use of measured bed load data for a period of 3 years to predict bed load of local rivers may provide unreliable estimates due to the short period of the measurement and bed load variability in time and space (Salemi et al., 2008). This notwithstanding seems to be a better option when compared against the alternative assumption of 10% of suspended sediment yield as bed load (Walling, 1984; Amisigo and Akrasi, 1997). However, the assumption of 10% of suspended sediment load as bed load was still used for all rivers with less than 200 km² catchment area due to lack of data. Also all rivulets and lagoon inlets with less than 10 km² catchment areas were considered potentially intertidal or lagoon-dominated and, therefore, no sediment yield estimates were assessed. The final estimated sediment yields obtained after the application of the regression in Eqs. (4), (5) and (7) to the rivers in the case study areas are presented in Table 2.

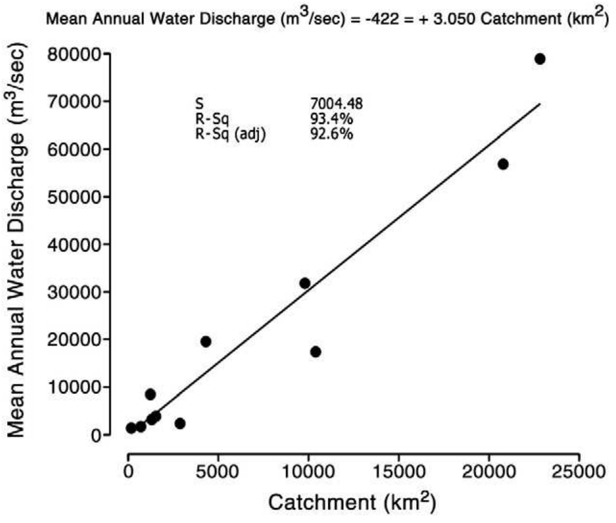


Fig. 11. Relationship between catchment areas and mean annual discharge of southern rivers in Ghana.

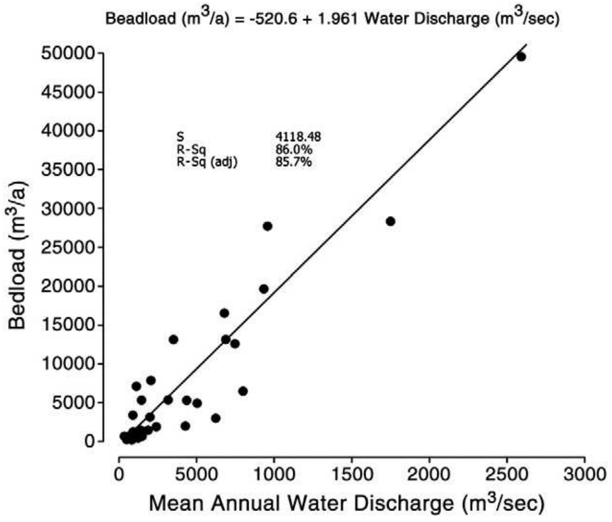


Fig. 12. Relationship between mean annual discharge and mean bed load of southern rivers in Ghana.

4. Results

Table 2 identifies all the coastal rivers and gives details of their catchment areas and the two components of sediment yield assessment for all rivers draining to the coast of Ghana. The rivers are sub-divided into three broad coastal divisions; the east coast, central coast and the western coast respectively (Fig. 13). On Table 2, names of rivers and streams that drain into lagoons have been indicated in parentheses after the names of the lagoons. Total sediment yield from each river represents the summation of mean suspended sediment yield and the mean bed load yield of the river per annum.

One important characteristic of fluvial sediment discharge to the coast is that only a proportion of the suspended sediment yield is significant to the beach. Beach sediment is composed of loose accumulations of sand, gravel or a mixture of both particles in various sizes. The grain size distribution of a beach sediment is usually asymmetrical and negatively-skewed toward medium and coarse grain size (about 84%), as a result of the removal of fine particles by wave and wind action (Bird, 2000). Proportions of suspended sediments are mostly carried away in suspension by wave and tidal currents to offshore, estuaries and coastal mudflats because they are very fine (below 63 μm).

Ayibotele and Tuffour-Darko (1979) identified, after taking 129 samples from different gauging stations that 50% of suspended sediment yield from rivers in Ghana are of grain sizes less than (63 μm). This implies that about 50% of suspended sediment yield from Ghana's rivers may not be useful for the beach because they are very fine and may be carried away to offshore or to estuaries and marshes down-drift (Milliman et al., 1985; Phillips and Slattery, 2006) and therefore total sediment yield considered to be useful to the coastal sediment budget assessment in this study represents 50% of suspended sediment yield plus the bed load from each river. However, this interpretation has been challenged by Cooper and Pontee (2006) who argued that the fine suspended sediment may be deposited in marshes and estuaries down-drift and, thus, has an important influence on the coast environment.

The rivers Volta, Pra and Ankobra in the east, central and west coast correspondingly (Table 2) had actual measured suspended sediment data and were among the sampled rivers used to derive the regression

Table 2
Sediment yield from coastal rivers in Ghana.

Location along the coastline	Names of coastal rivers, streams and lagoons from East to West coast	Catchment area (km^2)	Mean Suspended sediment yield (m^3/a)	Mean bed load yield (m^3/a)	Total fluvial sediment yield (m^3/a)	Sediment yield significant to the beach (m^3/a) β
Eastern coast (from Tema port Jetty to Ghana's Eastern borders with Togo)	Keta Logoon (Tordzie River)	2228	15,774	11,938	27,712	19,825
	Volta River	394,100	**@11,808,240**	***1,180,824**	**@12,989,064**	**@7,084,940**
			137,599,395	2,355,744	139,955,140	71,155,442
	Songor Lagoon	379	3671	879	4550	2715
	Mi River	80	722	*72	794	433
	Moyo Lagon	<10	#	#	#	#
	Afitsedor Lagoon	20	130	*13	143	78
	Gyankai Lagoon	160	1511	*151	1662	907
	Huape stream	<10	#	#	#	#
	Tanha stream	<10	#	#	#	#
	Laloi lagoon (Dawhe River)	185	1757	*176	1933	1055
	Gao lagoon (Gyrokorgyor stream)	15	81	*8	89	49
	Nsunedan Lagoon	<**10**	#	#	#	#
Central coast (from cape three points to Tema port jetty)	Sakumo Lagoon	77	692	*69	761	415
	Mokwe Lagoon	13	61	*6	67	37
	Songo Lagoon	12	51	*5	56	31
	Kpeshie Lagoon	37	298	*30	328	179
	Korle lagoon	52	445	*45	490	268
	Kyemu lagoon	<10	#	#	#	#
	Sakumo lagoon (Densu River)	2550	16,913	13,864	30,777	22,321
	Nyanya Lagoon	25	179	*18	197	108
	Dawa lagoon	<10	#	#	#	#
	Kako Lagoon	30	228	23	251	137
	Sumina lagoon	<10	#	#	#	#
	Saase Lagoon	<10	#	#	#	#
	Sefara lagoon	<10	#	#	#	#
	Ayensu lagoon (Ayensu River)	1700	16,699	8780	25,480	17,130
	Bosom Muna lagoon	<10	#	#	#	#
	Narkwa lagoon (Okyi Nakwa River)	1500	14,727	7584	22,311	14,948
	Amisa lagoon (Okyi Amisa River)	1370	13,444	6807	20,251	13,529
	Etsii Lagoon	25	179	*18	179	108
	Apa Lagoon (Bruku River)	125	1165	*117	1282	700
	Nfoa lagoon	15	81	*8	89	49
	Fosu lagoon	<10	#	#	#	#
	Kakum River	285	2743	317	3061	1689
	Benya lagoon (Anwin River)	45	376	*38	414	226
	Nsunedan Lagoon	<10	#	#	#	#
	Mpopro Lagoon	<10	#	#	#	#
	Brenu lagoon (Obuohu stream)	23	159	*16	175	96
	Susu lagoon (Abonka River)	156	1471	*147	1618	883
	Pra River	22,714	**@485,660**	***48,566**	**@534,226**	**@291,400**
			454,912	134,466	589,379	361,922
	Mpopro Lagoon	<10	#	#	#	#
	Brenu Lagoon	23	159	*16	175	96
	Susu Lagoon	156	1471	*147	1618	883
	Anta River	95	870	*87	957	522
	Anankwari River	57	495	*50	545	298
	Esuekyir	28	209	*21	230	126
	Hwin River	130	1215	*122	1337	730
	Onolimerem lagoon	<10	#	#	#	#
	Asukutia lagoon	<10	#	#	#	#
	Ata stream	15	81	*8	89	49
	Butre River	460	4469	1364	5833	3599
	Busua Stream	<10	#	#	#	#
Western coast (from Ghana western border with Cote D'Ivoire to Cape Three Points)	Nyila River	296	2852	383	3235	1809
	Erazule River	<10	#	#	#	#
	Ahumen Lagoon	13	61	*6	67	37
	Awanguzule lagoon	<10	#	#	#	#
	Ankobra River	8461	**@106,588**	***10,659**	**@117,247**	**@63,950**
			70,528	49,218	119,746	84,482
	Enhuli Lagoon	<10	#	#	#	#
	Amusure lagoon (Franza River)	840	8217	3637	11,854	7745
	Domini Lagoon	<10	#	#	#	#
	Dwuen Lagoon (Tano River)	26,489	617,128	157,045	774,173	465,609
Total yield	**Pre-Volta Dam (before 1964)**	**464,984**	**138,855,619**	**2,753,443**	**141,609,048**	**72,181,265**
Total yield	**Post-Volta Dam (post 1965)**	**464,984**	**13,064,464**	**1,578,523**	**14,642,972**	**8,110,763**

Notes on Table 1 above

* — 10% of suspended sediment yield was assumed as bed load.

\# — Catchment is less than 10 km^2 was assumed to be inter-tidal inlet rather than fluvial.

@ — Actual measured sediment yield (sources: FAO, 2005; Collins and Evans, 1986 for Volta River. Amisigo and Akrasi, 1997 for Pra and Ankobra).

β — Sediment yield significant to the beach is 50% of suspended sediment yield plus bed load (Ayibotele and Tuffour-Darko, 1979)

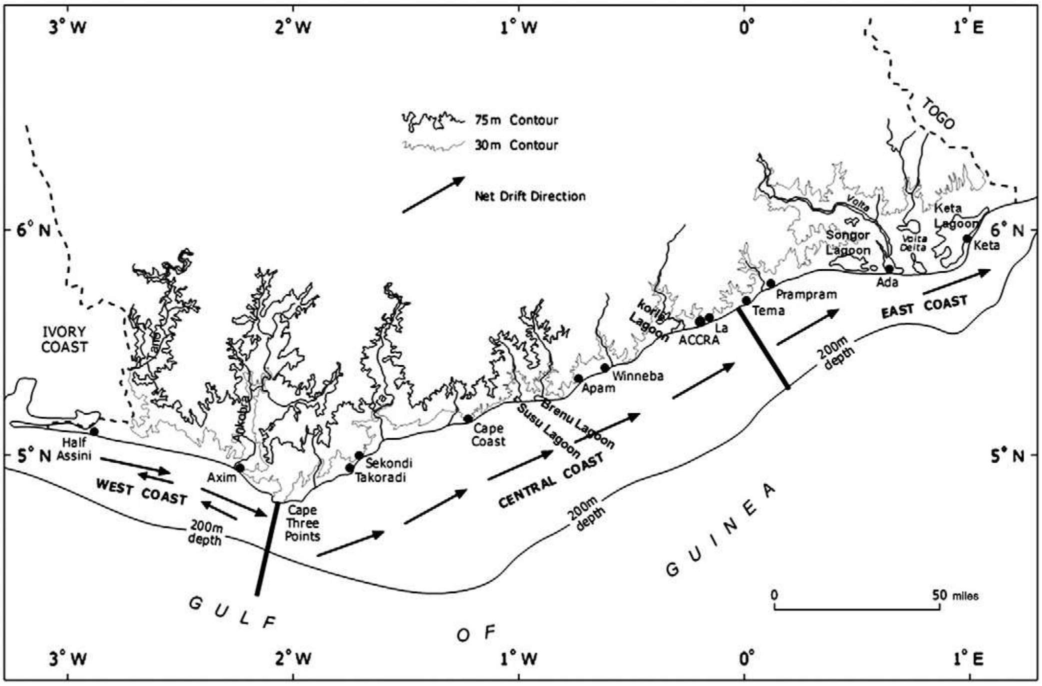


Fig. 13. The coastal map of Ghana showing net drift direction and coastal divisions.

equations for the suspended sediment load. Comparison of the measured suspended sediment yield from two rivers (Pra and Ankobra) and the yield from the regression equation estimates indicated that the model under-estimates suspended sediment yield from River Pra by 6% and River Ankobra by 33%. A comparison of the catchment size of the two rivers (Pra, 22,818 $km^2$and Ankobra 4268 km^2) revealed that the regression model (Eq. (4)) provides a slightly more reliable outcome for larger catchments than smaller ones. On the contrary, when the bed load was added to the suspended sediment yield, the models over-estimate total sediment yield by an average of 22% in both rivers. An observation from the bed load results of the two rivers suggest that the assumption of 10% of suspended sediment yield as bed load under-estimates bed load substantially. The confidence coefficient of the equations used for the estimation of suspended sediment yield was about 0.80 on the average and that of bed load was 0.86. On average, the total sediment yield estimates of all the rivers have an 83% confidence level.

It was identified that comparatively smaller basins have proportionally higher bed load than large basins. The results show that, on average, bed load of basins with catchment area between 200 and 2000 km^2 was about 56% of their suspended sediment, but bed load of large basins such as Pra, Tano and Ankobra was about 48% of their suspended sediment. An assessment of sediment yield from the model estimates for all rivers and sediment yield from the gauged rivers indicated that the models over-estimate yield from larger catchment areas (see the actual and estimated values of Rivers Pra and Ankobra) (Table 2) and under-estimates yield from smaller ones due to inadequate data, which led to the application of 10% of suspended sediment yield as bed load. However, it is commonly assumed that the over-estimated yields would be balanced out by rivers whose yields have been under-estimated (Milliman et al., 1999).

The total sediment yield estimate for Volta River by the regression model was about 140 million m^3/a. This amount is closer to those that other studies have quoted (153 million m^3/a) as the possible rate of sediment yield, were not for the interception by the Akosombo dam (Taylor et al., 2006). The actual post-dam sediment yield from the Volta River has been quoted by FAO (2005) as 12.9 million m^3/a (Table 2). This implies that, about 90% of the sediment yield from the Volta is intercepted by the Akosombo dam, which blocked about 95% of the drainage basin.

The results indicate that the Ghana coast is dissected by many south-draining rivers, stream and lagoons. More than 90% of total fluvial sediment supply to the coast is from four major rivers, the Volta, Pra, Tano and Ankobra, which therefore have significant effects upon their receptive sediment cells. By contrast, other fluvial inputs are significantly smaller and therefore likely to have only local effects upon their cells. The study identified that anthropogenic impoundment of fluvial sediment, particularly by the Akosombo dam, has reduced the total fluvial sediment input to the coast from about 71×10^6 m^3/a pre-Akosombo dam in 1964 to about 7×10^6 m^3/a at present (post-Akosombo dam). This sharp reduction threatened the stability of the East coast and has influenced an expensive ($83 million) defence scheme to be implemented to protect 8.4 km long coastline in Keta (Ellicott Dredges, 2000).

5. Discussion

The study has confirmed that some valuable fluvial data exist for Ghana's rivers but they vary with respect of quality and completeness due to the different methods of sampling and the purpose for collecting the data (Akrasi and Ayibotele, 1984). Nevertheless, no previous assessment has been made to estimate the fluvial sediment input to the coast and its influence on the coastal sediment budget. This study has demonstrated that the existing data are a useful resource for further investigation into sediment discharge of rivers in Ghana despite the problems of uniformity and completeness of the data.

This study has revealed that, generally, rivers in Ghana before 1964 contributed sediment above 72×10^6 m^3/a to maintenance of beaches and coastal stability in Ghana (Table 2). However, growing impacts of anthropogenic impoundment have caused major reduction of the fluvial sediment input to the coastal sediment budget which is a little above 8×10^6 m^3/a at present. It is important to highlight that both the gauged measurements and the model estimates of fluvial sediment yield did not account for certain factors that prevent fluvial sediment from reaching the coast. The estimated values of fluvial sediment supply given in this study include potential deposits in estuaries, lagoons and other depositional features beyond the sample stations downstream. It is assumed that potentially some fluvial sediment might be stored in those depositional features on the lower course of the river — between the sample stations and the coast (Milliman et al., 1985; Lambert and

Walling, 1987; Phillips and Slattery, 2006). Other contributing factors include interception by small dams and check dams on small ungauged rivers (Vörösmarty et al., 2003).

The major quantities of sediment trapped by large reservoirs and their effects on the morphology of the lower courses of rivers and the coastal sediment budget are believed to be a global phenomenon (Vörösmarty et al., 2003; Ali and De Boer, 2007; Burroughs et al., 2009). For instance, it is estimated that, before the construction of the Akosombo dam in 1964, the Volta River supplied over 71×10^6 m^3/a of sediment significant to the beach. However, the dam had reduced the amount to about 7×10^6 m^3/a (Table 2). This halted the historical pattern of river delta accretion. Coastal erosion along the coastline east of the present Volta mouth was quoted to be around 8 m/year between 1964 and 1975 (Ly, 1980). According to Ly (1980) and Armah (1991), the high rate of coastal erosion on the eastern coast was caused by the impacts of damming of the Volta which was the main source of sediment supply to that part of the coastline. Numerous minor defence schemes developed over the years to halt this high rate of erosion east of the Volta delta were ineffective (Armah, 1991). Keta was almost destroyed by erosion prior to construction of a major defence project and reclamation work that was completed in 2002 (Nairn and Hayes, 1997; Nairn et al., 1998; Boateng, 2009).

The impact of Akosombo dam on the sediment yield from the Volta River and the subsequent effects down-drift clearly demonstrate the importance of fluvial sediment input to some sections of Ghana's coast. This indicates that the plan to build dams on Rivers Pra and Ankobra (Kufuor, 2007), which contribute fluvial input of about 3×10^5 m^3/a and 64×10^3 m^3/a, respectively, to the coast could have a negative impact on the coastline, especially the coastal towns immediately down-drift of their estuaries. Implementing such a political decision without full assessment of the potential impacts on the coast or without development of remedial measures to deal with the impact could have similar deleterious effects on the coastal settlements and developments down-drift, as was experienced on the Volta delta.

This study has indicated that rivers with small catchment size (between 50 and 5000 km^2) supply significant amount of sediment to the coast (Table 2). This confirms the fact that small rivers generally discharge much greater loads relative to their drainage basin areas than large rivers (Milliman and Syvitski, 1992). The reason for this phenomenon is based on the fact that smaller basins have steeper gradients, less storage capacity, less abraded materials, and greater response to episodic events, such as floods and landslides (Milliman et al., 1999).

Sediment yield significant to the beach (last column of Table 2) was estimated in addition to total sediment yield since it was estimated that probably about 50% of suspended sediment yield in Ghana are very fine particles and may not be significant to the beach (Ayibotele and Tuffour-Darko, 1979). However, very fine particles which are normally not considered significant to the beach coastal sediment budget can be transported in suspension and deposited in estuaries and marshes down-drift, and therefore should be accounted for in the overall coastal sediment budget (Cooper and Pontee, 2006). Marshes are important in natural coastal protection, especially on these tropical mangrove coasts.

The study has revealed that the assumption of 10% of suspended sediment yield as bed load is not always correct as bed load of the sampled rivers range between 10% and 56%. Kusimi (2008) identified that this occurs because much of the bed load is either abraded or deposited (hydraulic sorting) as the materials are transported downstream. Hence, holding all other factors constant, rivers with longer catchments tend to have lower bed load than shorter catchments. This also confirms the conclusion of Knighton (1998) that particle size decreases with distance downstream; therefore, longer rivers tend to supply more fine sediment to the coast than shorter rivers.

It could be argued that, given the computed volume of fluvial sediment contribution to the coastal sediment in Ghana and holding other factors constant, significant reduction of fluvial sediment supply to the coast could potentially cause coastal instability. It suggests that it is important to develop detailed understanding of the exact connections between key fluvial sediment inputs and coastal stability through full sediment budget analysis. Such knowledge could serve as a key input to the development of sustainable shoreline and catchment management policies.

6. Conclusion

This study clearly shows the importance of quantifying sediment yield from all coastal rivers within a region and the need to understand the possible impact each major coastal river could have on the coast if its sediment supply alters. Such alteration can be anticipated to occur in future due to human activities and climate change. The impacts of the Akosombo dam on the east coast of Ghana have indicated that sections of the coast are very closely connected to the hinterland through the fluvial sediment input from rivers. Therefore, development in the hinterland that alters the fluvial sediment input from the local rivers could have significant effects on the coast. This indicates the need to document understanding of the connections between the coast and the local rivers through comprehensive sediment budget analysis and also to ensure that catchment management plans and coastal management plans are integrated or interconnected.

The attempt to assess the fluvial sediment yield from all coastal rivers in Ghana was hindered initially by inadequate direct measured data. This hindrance is not uncommon in many countries of the world (McClelland et al., 2004; Nilsson et al., 2005; Hunger and Doll, 2007). However, the problem was overcome by the application of a regression approach, which provides an estimated sediment yield for non-gauged rivers based on data from gauged rivers and so maximises the value of existing data. It should be noted that such approaches need to be applied with care and are only feasible where it can be shown there are strong regional correlations for discharge and sediment load as demonstrated in this study (Figs. 5, 6, 7, 8).

The estimates of fluvial sediment yield that are significant to the beach (Table 2) may have elements of uncertainties based on the fact that the regression model does not account for factors such as storage in lagoons, estuaries and lower river valleys down-stream of the gauged station and interception by check dams. Not only this but also the regression equations used for the estimates have a confidence level of 83% suggesting some margin of error with the estimates. Notwithstanding these uncertainties, the study provides a detailed and holistic assessment of fluvial sediment contribution to the coastal sediment budget in Ghana, which has never previously been investigated.

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