

Development of a sediment yield model for Ghana using sediment transport data

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Abstract Soil erosion is one of the most pressing issues facing developing countries. In Ghana, a country with an expanding population and high potential for economic growth, agriculture is an important resource. The high intensity seasonal rainfall coincides with the early growing period of crops such as maize, yam and cassava. Agricultural plots are very susceptible to high erosion rates, especially when on steep sided valleys in the region around the south of Lake Volta. Thus, accurate prediction of soil erosion is a necessity. The accuracy of soil erosion models is largely determined by the availability and quality of the sediment yield data used for calibration. A conceptual model based on the CALSITE model is being developed to run in the GRASS GIS package for use in Ghana. The model is being tested on a 14 km² basin southwest of Lake Volta, where streamflow, rainfall, soil moisture and sediment transport data were collected during September 2000.

Key words CALSITE; conceptual modelling; Ghana; sediment transport; sediment yield; soil erosion

INTRODUCTION

Soil erosion is one of the most pressing issues facing developing countries. Accurate modelling of soil erosion to predict, and thus propose, methods to slow rates of erosion is important because a successful and productive agricultural base is necessary for economic growth. To model erosion, good quality sediment transport data that has been accurately measured are required for calibration. Sediment transport rates are important as they can provide sediment yield data, which is the most effective indicator of the negative effects of soil erosion. However, as stated by Bradbury *et al.* (1993), the prediction of sediment yield in developing countries is usually difficult because of the lack of suitable data and an appropriate predictive technique.

In Ghana, a country with an exponentially expanding population and high potential for economic growth, agriculture is a vital resource. In some areas, most of the crop production is low technology and restricted to shifting cultivation with most units effectively being self-sufficient smallholdings, which trade the surplus in the large urban areas and towns. Small-scale cash crop production, such as cocoa beans, is also undertaken. High intensity seasonal rainfall coincides with the early growing period for many of the crops such as maize, cassava and yam. This means that the plots are very susceptible to high erosion rates, especially when combined with farming areas on steep-sided valleys in the regions around the southern half of Lake Volta. According to Hens & Boon (1999), the environmental situation in Ghana is characterized by desertification, land degradation, soil erosion and inadequate water supply.

The purpose of this report is to summarize development, so far, of a conceptual soil erosion model for Ghana that will calculate sediment yields from drainage basins using a GIS and to discuss the issues involved in the coordination of sediment transport measurements and sediment yield predictions. The key objectives in developing the model are: (a) to calibrate and test the model on a small 14 km² drainage basin south of Lake Volta containing a tributary of the River Pompom, then (b) to apply the model to much larger rivers and basins around Lake Volta to calculate the siltation rates of the lake, the drainage area of which comprises about 70% of the country.

Background and history

Many of the key environmental issues facing Ghana can be summarized from Hens & Boon (1999) as follows. Annual loss of forest cover over the whole of the country is estimated at 22 000 ha. The clearing of forests using bushfires leads to low agricultural yields, which in turn put more pressure on the land to be used for cultivation. The need for high quality agricultural land is important in a country where the agricultural sector accounts for more than 40% of the GNP and from which 75% of the population earns its living. In addition, soil erosion caused by poor agricultural management is causing increased sediment loads in rivers and suspended particles in water bodies.

According to Bradbury *et al.* (1993) the initial distinction in modelling is between deterministic and stochastic models. However, there are very few stochastic soil erosion models. Deterministic models can be classified in to two main categories: empirical models and physically based models; a third category: conceptual models describes those that are somewhere between the two, i.e. they contain some parts that are empirically derived and some that are based on mathematical representations of the physical processes. Physically based and conceptual models both have their own distinct advantages and drawbacks especially when utilized in developing countries; these are summarized in Table 1.

Beuselinck *et al.* (1998) state that quantitative description of sediment transport across areas of deposition is an essential part of assessing the off-site effects of soil erosion on hillslopes. They also state that an understanding of sediment delivery from hillslopes to the stream requires information on both soil erosion and sediment deposition. Thus, sediment transport formulae have become the governing equations within modern soil erosion/sediment yield models such as EPIC (Williams *et al.*, 1984), AGNPS (Young *et al.*, 1987), SWAT (Arnold *et al.*, 1993) and WEPP (Flanagan & Laflen, 1997).

Table 1 Advantages and disadvantages of different model types.

Model type	Physically based	Empirical
Advantages	Can be calibrated using only short data sets. Adaptable to other situations.	Simplistic and easy to use. Require only a few input parameters.
Disadvantages	Require large number of input parameters not always available. Complex to use.	Require extensive data sets for calibration. Not always applicable to other basins.

Field work

During September 2000, a field trip to Ghana was undertaken to collect field data for a small basin as well as obtaining sediment data from the Water Resources Research Institute for some large-scale basins that was collected during the 1980s and 1990s. Using data provided by the Soil Research Institute (SRI), Accra, Ghana, a study basin was selected from the area to the south of Lake Volta where the most at risk areas had been identified using the Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1978). The location of the selected basin is shown in Fig. 1. Figure 2 shows the USLE results of southern Ghana in $t\ ha^{-1}\ year^{-1}$.

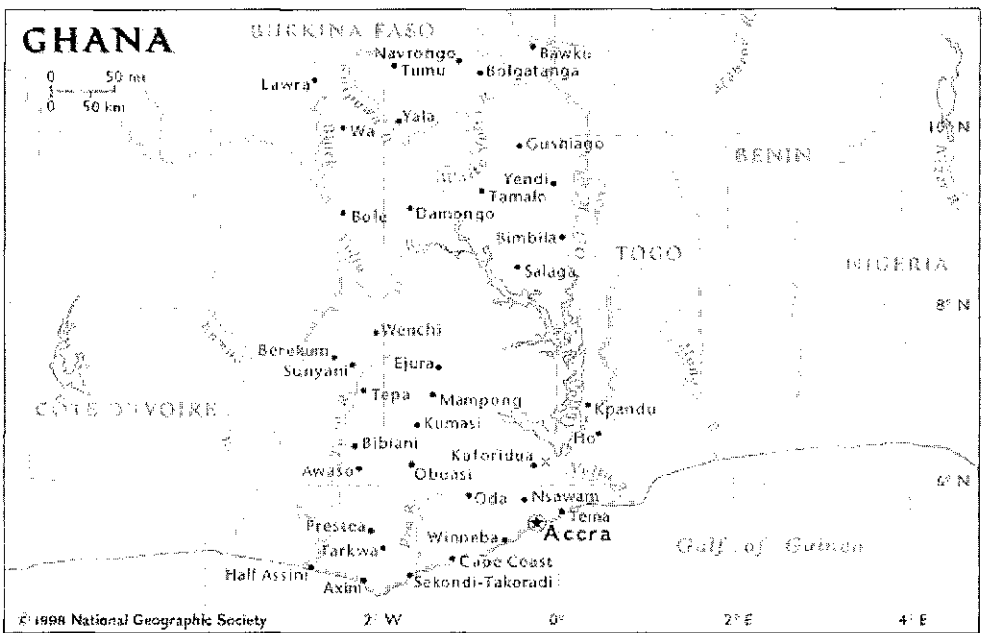


Fig. 1 Map of Ghana showing the location of the study basin (x) (Xpeditions, 1998).

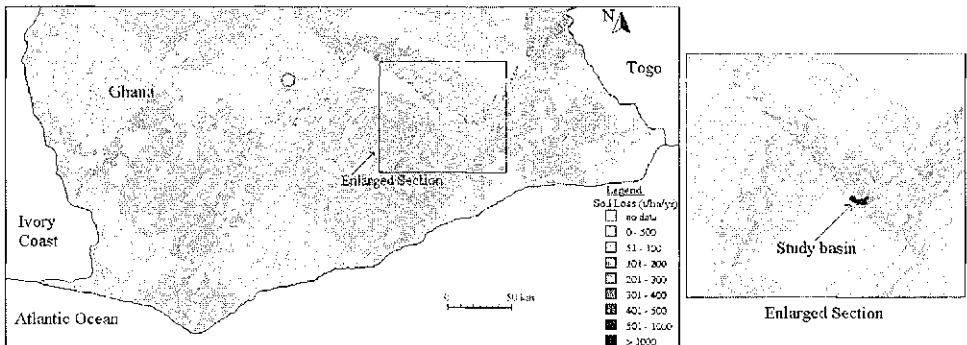


Fig. 2 USLE analysis of Southern Ghana with an enlarged section showing the location of the study basin.

The basin was then monitored over a two-week period, during the start of the September–December rainy season, for daily rainfall, streamflow, sediment load, and soil moisture readings. Sediment concentrations in suspended loads were measured at the outlet using daily bottle samples and bed loads were measured using pit traps. The results were then used to calculate sediment transport rates and thus sediment yield from the basin.

The basin contains two major soil types, the area is dominated by a Gleyic Arenosol (FAO, 1990) and in the southwest, a Haplic Nitisol (FAO, 1990) is found. The Arenosol is a loamy sand, the Nitisol a sandy loam, both types having a sand content of approximately 75%. Data were collected for the 14 km² basin during September and included events with rainfall accumulation ranging from 10 to 61 mm.

Theory and structure of the model

After considering the advantages and disadvantages of the modelling techniques, it was decided to develop a conceptual model that incorporates aspects of both types of model.

Figure 3 shows the structure of the model broken down into three main sections.

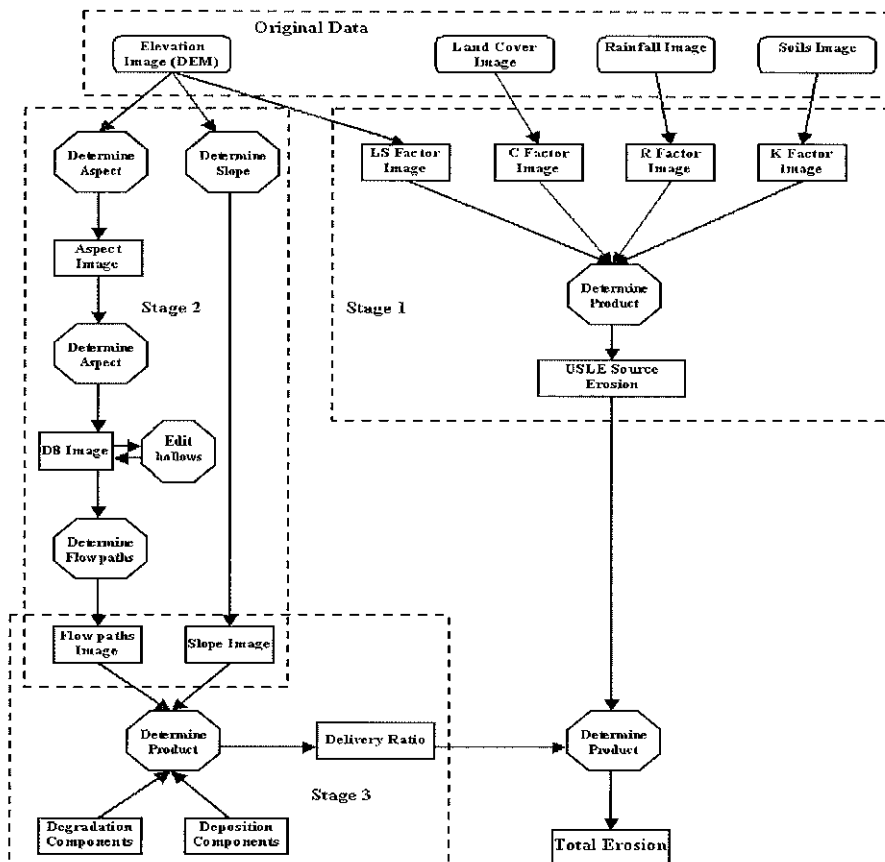


Fig. 3 Flow diagram of the model.

The model is based upon the CALSITE model, which was chosen because of its effective routing structure and its use of a sediment delivery ratio (SDR), a readily calibrated component. The SDR is adapted to incorporate sediment transport equations giving more accurate sediment yield predictions.

The first stage deals with the calculation of source erosion using the USLE, the various factors derived from the original data images. The USLE has already been established as an effective calculator of soil loss at source and has been used in many models as a predictor of source erosion such as ANSWERS (Beasley *et al.*, 1982) and AGNPS (Young *et al.*, 1987). Stage two creates the routing structure of the model that can incorporate simple single flow direction routing models such as the d8 algorithm (O'Callaghan & Mark, 1984) or complex multi flow direction routing algorithms like the FD8 algorithm used in the TAPES-G model (Wilson & Gallant, 1998). The final stage of the model is the calculation of the SDR. The SDR for each cell in the basin is a function of the transport capacity of that cell. The sediment transport equations provide the link between the soil loss and sediment yield defining the transport capacity of the basin.

The transport capacity is defined as $T = f(Q, DEP, DEG)$, where Q is the function of runoff volume, DEP is a function of the rate of deposition of sediment from stream-flow and DEG is a function of the rate of degradation of the soil over which flow passes. DEP and DEG are defined by sediment transport equations. Q can be analysed either on an annual basis, in which case it is a function of the annual runoff volume (which can be empirically related to annual rainfall), or on a daily/single storm basis, when it is a function of peak flow rate. The parameters Q , DEP and DEG can be varied to incorporate many different parameters and equations.

Programming and software

The GIS system being used for the modelling process is an open source software package, the Geographical Resources Analysis Support System (GRASS) available on the GNU public licence. The program is available as source code and is well documented, which enables modellers to develop and program their own models to be run within the GRASS environment. A number of existing sediment yield models are available under GRASS, including ANSWERS (Beasley *et al.*, 1982) and AGNPS (Young *et al.*, 1987).

RESULTS AND DATA

USLE estimates have already been calculated for the whole of southern Ghana and this provided a basis for the selection of the study basin. The most basic form of the USLE was used, $A = R C K LS$, where R is the rainfall erosivity factor, C is the crop cover factor, K is the soil erodibility factor, and LS the slope length factor. Figure 4 shows the current land use within the basin and the associated C factors. Using the basic CALSITE model to calculate the total transport of sediment due to erosion over the whole year gives a total of 4353 t year^{-1} . Figure 5 shows the resultant erosion across the basin. Table 2 shows some example data from the study basin.

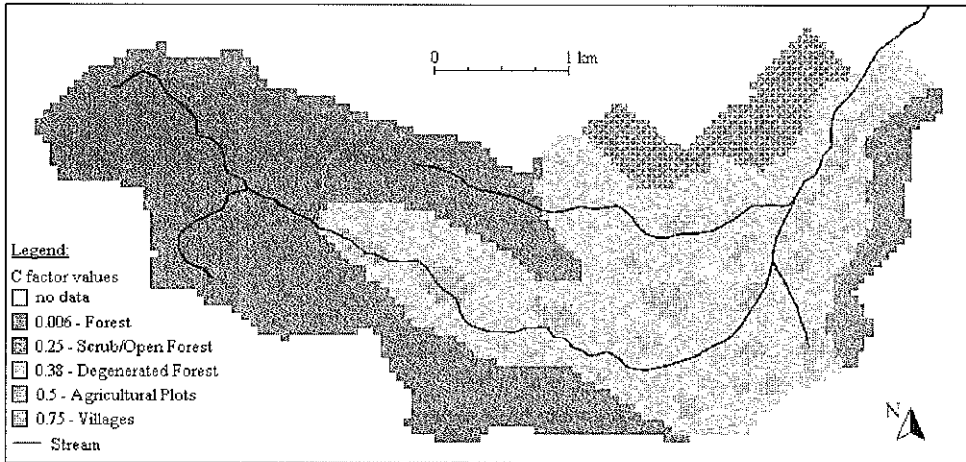


Fig. 4 Land use and C-factors in the study basin.

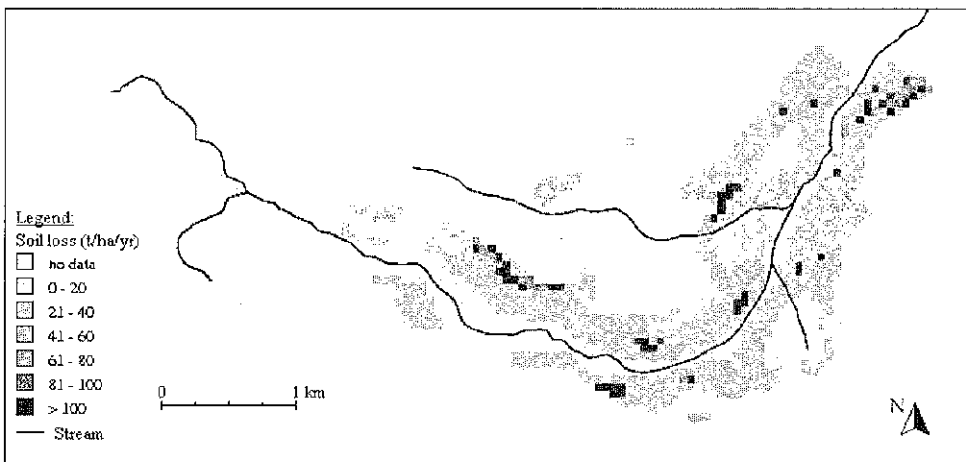


Fig. 5 Total transported sediment from each grid square, calculated using CALSITE ($t\ ha^{-1}\ year^{-1}$).

Table 2 Example data collected from the study basin.

Date	Rainfall (mm)	Total suspended load (t/storm)	Total bed load (t/storm)
15 September 2000	1.1	0.009	0.615
19 September 2000	61.4	3.673	82.116
20 September 2000	10.8	0.146	14.925
21 September 2000	5.1	0.040	2.277

DISCUSSION AND FURTHER WORK

Ghana is one such country where there the potential for significant soil erosion to occur exists. The situation could become much worse if steps are not undertaken to

control rates of erosion. The country is one of the more advanced developing countries, and with an expanding population and therefore a greater demand on agricultural productivity, it is vital that soil erosion is monitored and controlled so that this demand can be met.

Accurate sediment transport measurements can provide reliable estimates of sediment yield, enabling the effective prediction of both soil erosion from upland areas and the siltation rates of lowland areas, river estuaries, reservoirs and lakes. However, in the future this will rely much on the cooperation between soil erosion modellers and sediment transport measurers.

Further work on the model will involve the improvement of the two most sensitive and important parts of the model, the SDR and the routing algorithm. Work on the SDR will consist of the programming and testing of many different sediment transport equations such as Van Rijn (1984) and Hossain (1987) and concepts such as those used in SWAT and EPIC. There are also several methods available for the routing algorithm. The various options will be tested and analysed to determine which combination gives the results that best fit the data collected.

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