Journal of Spatial Hydrology
Vol.6, No.1 Spring 2006

Estimating Spatial Sediment Delivery Ratio on a Large Rural Catchment

Benedict M. Mutua[1, 2] and Andreas Klik[1]

Abstract

Soil erosion and sediment yield from catchments are key limitations to achieving sustainable land use and maintaining water quality in streams, lakes and other water bodies. Controlling sediment loading requires the knowledge of the soil erosion and sedimentation. However, sediment yield is usually not available as a direct measurement but estimated by using a sediment delivery ratio (SDR). An accurate prediction of SDR is important in controlling sediments for sustainable natural resources development and environmental protection. There is no precise procedure to estimate SDR, although the USDA has published a handbook in which the SDR is related to drainage area. This paper presents a new approach for estimating spatial sediment delivery ratio (SDR) for large rural catchments. The SDR is predicted using a Hillslope Sediment Distributed Delivery (HSDD) model in conjunction with a physically distributed hydrological model in a GIS environment. The new approach was developed and tested on Masinga catchment, a rural large catchment in Kenya. The hydrological model was validated using predicted and observed daily stream flows and a performance criterion based on Nash Sutcliffe coefficient of model efficiency was used. The developed model is not only conceptually easy and well suited to the local data needs but also requires less parameters, which offer less uncertainty in its application while meeting the intended purpose.

Keywords: soil erosion, sediment yield, sediment delivery ratio, modelling, Masinga catchment, GIS, hillslope

Introduction

Soil erosion models such as the Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978) and the Revised Universal Soil Loss Equation (RUSLE) (Renard et al. 1997) estimate gross soil erosion rate at plot-scale. Erosion rates estimated by USLE are often higher than those measured at catchment outlets. Sediment delivery ratio (SDR) is used to correct for this reduction effect. SDR is defined as the fraction of gross erosion that is transported for a given time interval. It is a measure of sediment transport efficiency, which accounts for the amount of sediment that is actually transported from the eroding sources to a measurement point or catchment outlet compared to the total amount of soil that is detached over the same area above that point. In relatively large catchments, most sediment gets deposited within the catchment and only a fraction of the soil that is eroded from the hillslope reaches the stream network or the catchment outlet.

Many factors are addressed when calculating this ratio. The factors that influence the SDR include hydrological inputs (mainly rainfall), landscape properties (e.g., vegetation, topography, and soil properties) and their complex interactions at the land surface. The multitude of such interactions makes it difficult to identify the dominant controls on catchment sediment response. In reality, erosion is not normally measured directly. It is measured as sediment yield at a small scale, such as a

---

[1] *University of Natural Resources and Applied Life Sciences (BOKU)*
Institute of Hydraulics and Rural Water Management, 18 Muthgasse, 1190 Vienna, Austria.
[2] *Egerton University, Department of Agricultural Engineering, Box 536, Njoro, Kenya.*
Corresponding author. E-mail address: bmmutua@yahoo.com

hillslope plot. Thus SDR is a scaling factor used to accommodate differences in area-averaged sediment yields between measurement scales (Dickinson and Collins 1998). Physically it stands as a mechanism for compensating for areas of sediment deposition that become increasingly important with increasing catchment area.

There is increasing interest in improving water resources development, catchment management, land use and land productivity. Problems caused by soil erosion and sediments include loss of soil productivity, water quality degradation, and less capacity to prevent natural disasters such as floods (Novotny and Olem 1994). Sediment yield is a critical factor in identifying non-point source pollution as well as in the design of the construction of hydro structures such as dams and reservoirs. However, sediment yield is usually not available as a direct measurement but estimated by using a sediment delivery ratio (SDR).

Presently available prediction models are not generally applicable to particular catchments especially large rural catchments. A case in point for such large catchments is the Masinga catchment. This catchment has one of the main reservoirs in Kenya designed for hydropower generation but it is faced with severe sedimentation that has reduced its designed capacity by more than 10% (Saenyi 2002). Yet little research has been done on the prediction of spatial sediment delivery ratio in the catchment.

Commonly used SDR methods

At regional scale, the most widely used method to estimate SDR is through an SDR-area power function given as:

$$SDR = \alpha A^{\beta} \tag{1}$$

Where A is the catchment area (km^2), the constant α and a scaling exponent β are empirical parameters (Maner 1958; Roehl 1962). Field measurements suggest that β is in the range –0.01 to –0.025 (Walling 1983; Richards 1993), which means that SDR decreases with increasing catchment area. The scaling exponent β contains key physical information about catchment sediment transport processes and its close linkage to rainfall-runoff processes. It seems that β decreases with increasing aridity (Richards 1993). However, field data from studies carried in different catchments of the world show that the relationship between SDR and drainage area changes considerably for each catchment. Extrapolation of these empirical relationships can be misleading and could result in SDR exceeding 100%.

A number of methods by different researchers have been in use to estimate the SDR. Some estimates of SDR are based on the drainage area and the distance referred to as SDR Vs area and SDR Vs distance curves respectively. For instance, Renfro (1975) developed an equation relating SDR with the drainage area. It is based on Maner's (1958) equation. Vanoni (1975) used the data from 300 watersheds throughout the world to develop a model by the drainage area power function. The USDA SCS (1979) developed a SDR model based on the data from the Blackland Prairie, Texas and developed a power function derived from the graphed data points. Other SDR models have been based on the rainfall-runoff factors for instance, a SDR model, which is used in the Soil and Water Assessment Tool (SWAT) (Arnold et al. 1996), takes runoff factor into account. SDR models have also been based on slope, gradient, relief-length ratio and on particle size. For example, Williams and

Berndt (1972) used slope of the main stream channel to predict sediment delivery ratio. Maner's studies (1958) suggested that SDR was better correlated with relief and maximum length of a watershed expressed as relief-length ratio (*R/L*) than with other factors and Williams (1977) found the sediment delivery ratio is correlated with drainage area, relief-length ratio, and runoff curve numbers. Sun and McNulty (1988) and Yagow et al. (1988) estimated SDR based on distance and distance-slope equations respectively. Walling (1983) suggested that sediment delivery ratio could be calculated from the proportions of clay in the sediment and in the soil.

Limitation of the existing SDR estimation methods

The SDR-area relationship does not take into account local descriptors, such as rainfall, topography, vegetation, land use and soil characteristics. There are other empirical relationships which show that SDR varies with various physiographic attributes but the data required in these relationships are few and only of local extent (Khanbilvardi and Rogwski 1984). This limits the usefulness of such a lumped approach.

The traditional SDR methods are often data-driven. They depend on the existence of long periods of sediment yield records at the stream gauging stations and a sensible measure or estimation of hillslope erosion rate. However, there are a few consistent long periods of sediment yield data available in the Masinga catchment to allow such an analysis to be carried out. In addition, approaches based on analysing sediment yield records cannot identify the separate effects of changing climate, land use and management practices on sediment delivery as catchment response to change is often longer than the record time.

It is known that there are some limitations of using the general SDR methods (Walling 1983; Richards 1993). One is these SDR methods cannot explicitly predict the locations and rates of sediment deposition in the lowland phases, and another is the problem of temporal and spatial lumping and lack of physical basis.

Moreover, most procedures were developed to determine the SDR based on runoff models for small scale catchments, which cannot be applied in the current study since the catchment in question is large (6,255 km^2). In addition, there is little sediment yield data available within Masinga catchment to be used to calibrate the parameters of the SDR-area based models. Field measurement of sediment is severely limited within Masinga catchment. The existing measurements in this area are at much smaller scales and in a few runoff plots and cannot be relied upon to estimate SDR in a spatial domain. Faced with such a limitation, the solution lies in developing a spatially distributed sediment delivery model.

Recent development in this direction is towards the spatially distributed modelling using GIS techniques (Ferro and Minacapilli 1995). In the recent past, the concept of runoff travel time has been used to estimate the SDR. For example Ferro and Porto (2000) modelled erosion and spatially distributed sediment delivery in a watershed based on the travel time concept. This approach was incorporated into a GIS by Jain and Kothyari (2000). Fernandez et al. (2003), also estimated water erosion and sediment yield for the Lawyers Creek Watershed using RUSLE, GIS and a model based on the travel time concept.

This study therefore, attempts to develop and apply a spatially distributed sediment delivery model in a GIS environment. The GIS is used to generate and determine the values of factors in the model. One of the objectives of this study is to develop an SDR model that incorporates the key elements of the catchment storm response and sediment delivery process. The way that catchment response time varies with catchment area depends on the relative dominance of hillslope response, channel hydraulic response, and network of geomorphology.

Objective

The main objective of this study is to formulate a physically distributed SDR model and test the model on Masinga catchment, a large rural catchment in Kenya.

Materials and Methods

Study area

The Masinga catchment area is some 6,255 km^2 in extent, lying to the east of the Aberdare Mountains and south of Mount Kenya. It lies between latitudes 0° 7' South and 1° 15' South and longitudes 36° 33' East and 37° 46' East. The geology of Masinga area can be broadly divided into volcanic rocks in the north and west, and pre-cambrian basement complex in the Southeast. The landform in the catchment ranges from steep mountainous terrain with strong relief in the west, to undulating plains with subdued relief in the Southeast. The elevations above mean seal level (asl) in the mountainous terrain range from 2500 to 4000 m and for the undulating plains from 900 to 1200 m. The soils are generally Lithosols and Histosols (FAO classification) at the highest altitudes in the Aberdare with Humic Andosols at slightly lower elevations. Over much of the rest of the basalt foot slopes, deep fragile clays (Eutric Nitosols) predominate. On the basement complex, the soils are mostly coarser textured and shallower and are classified as Acrisols, Luvisols and Ferralsols.

The catchment falls within five agro-climatic zones, ranging from semi-arid in the east to humid near the western side. The annual rainfall is bimodal with short rains occurring from September to November and the long rains from March to May. The mean annual rainfall vary from about 600 mm on the easterly boundary to over 2000 mm on the Aberdare Mountains. The maximum temperatures vary from 25.5° C to 31.0° C generally being experienced in February or March, prior to the onset of the main rain season (long rains). Minimum mean temperatures of 21.0° C to 24.0° C occur in the month of July.

The catchment has an estimated population of about 2 million people (1999 census) with most people engaged in agricultural activities. Almost all the cultivation takes place in the Southeast, Northwest and generally in the western areas. There is scattered cultivation in the eastern half of the area with slopes greater than 15% where the soils are Vertisols and where severe erosion is taking place. The remainder of the area is used for grazing with large numbers of cattle, sheep and goats being herded on the area, which is almost completely denuded of grass and with very little cover.

Hydrological modelling using ArcView GIS

There are a number of hydrologic models in existence today. These differ mostly in the hydrologic variables of concern and in the space-time region of model application. Catchment models tend to concentrate on the catchment as the basic hydrologic unit since this entity serves as a hydrologic control volume (Bras 1990).

The advent of object-oriented GIS programming languages has broken the barrier to capturing time variation of spatial processes that was so great a limitation in earlier GIS applications to hydrology. Various methods for creating GIS-based models of hydrologic processes are emerging but they have not yet been standardized to the point that they can be applied widely. The integration of hydrologic processes, particularly integration of surface and groundwater flow, is not yet solved very well. As well, integration of processes across scales of space and time is not well understood but advances are being made to address this limitation.

In today's environmental engineering practice, many computer models have been developed to estimate the amount of sediment yields in lakes, estuaries and rivers. In addition, advancements have been made in determining the pollutants, which enter those water bodies. However, the connection between the spatial sediment sources to the in-stream sediment amount has not been properly addressed. Most water quality models concentrate just on modelling the system once the sediments and other pollutants have reached the receiving waters, while many pollutant models never route the loadings into the water bodies. This lack of continuity presents a need of a method in order to link the spatially based sediment source characterisation with the water quality modelling of the receiving waters. A link would provide an easier way to examine the cause and effect relationship, which exists between these two areas. To establish such a connection, a system, which can allow spatial representation of parameters, is needed. With this type of system, the spatial modelling of the land surface to determine such parameters as non-point source pollutant loadings would be possible, along with the storage and manipulation of water quality modelling data.

Development of HSDD model

A simplified sediment transport model that does not require a lot of hydrological data, which is not available for Masinga catchment, was developed for this study. The developed model is known as the Hillslope Sediment Delivery Distributed (HSDD) model. The HSDD Model was developed to predict the Spatial Sediment Delivery Ratio (SDR) in order to determine the sediment yield reaching the stream network and other water bodies within Masinga catchment.

The HSDD model requires the discretisation of the catchment into morphological units (i.e., areas of defined aspect, length, steepness) to determine the spatial sediment delivery ratio (SDR) for each unit. The model assumes that the catchment is sub-divided into homogeneous sub-catchments (hydrological units) based on hydrological and landscape parameters. The most important layer is the digital elevation model (DEM), which the model uses to define the sub-catchments, assign identification numbers, and determine their areas.

The approach in this study was to develop a relationship between the sediment delivery ratio (SDR) using the sediment travel time as a function of the overland flow and channel flow, and sub-catchments' responses based on rainfall, evaporation, land cover and soil properties. The developed sediment delivery ratio model was aimed at incorporating the required SDR parameters in a cell-by-cell calculation of uniquely specific derivations for changes over space. The model was developed to maintain a lumped parameter of time, assuming that the supply remains constant for each time step (one day), yielding an average annual estimate of sediment yield. The relationship between SDR and the sediment travel time by the HSDD model is given as:

$$SDR = \exp(-\beta T_{ic}) \qquad (2)$$

Where β is sub-catchment response coefficient, T_{ic} is the sum of the overland flow travel time t_o and the shallow concentrated flow travel time t_c of the sediment.

It was assumed that the sediment that reaches the stream network takes the same travel time as the runoff. The flow length was determined by using the flow direction and flow accumulations grids that were determined from the DEM. The time for runoff water to travel from one point to another over the catchment was determined using the flow distance and velocity along the flow paths. This is expressed as:

$$t_i = \sum_{i=1}^{N_p} \frac{l_i}{v_i} \qquad (3)$$

Where t_i is the travel time (hr) for cell *i*, l_i is the length of segment *i* in the flow path (m) based on the flow direction, v_i is the flow velocity for the cell *i* (m/s) and N_p is the number of cells traversed by runoff from cell *i* to the nearest channel.

For a cell *i*, the cumulative travel time was estimated by summing the travel time along its flow path. More specifically, if a sediment particle in cell *i* travelled through n_o cells overland and n_c cells in the stream (shallow channels) to reach the sub-catchment outlet, then the overland travel time t_o was used in each of the n_o upland cells and to calculate the concentrated shallow flow travel time t_c was used in each of the n_c stream cells and aggregated to estimate total flow travel time (T_{ic}).

In this model, it was assumed that the sediment particle travelled along the paths of the runoff water. The runoff was routed from the hillslopes to the stream network. The model estimated the runoff using the Soil Conservation Service Curve Numbers (SCS CN), which were determined from the land use/ land cover and the hydrological soil groups for each sub-catchment. The Manning roughness coefficient and coefficient of velocity for each sub-catchment were based on the hydrological and land use/ land cover type. Estimates from relevant literature were used to assign these coefficients. The conceptual procedure to estimate the cumulative travel time of the sediment based on the HSDD model is shown in Figure 1.

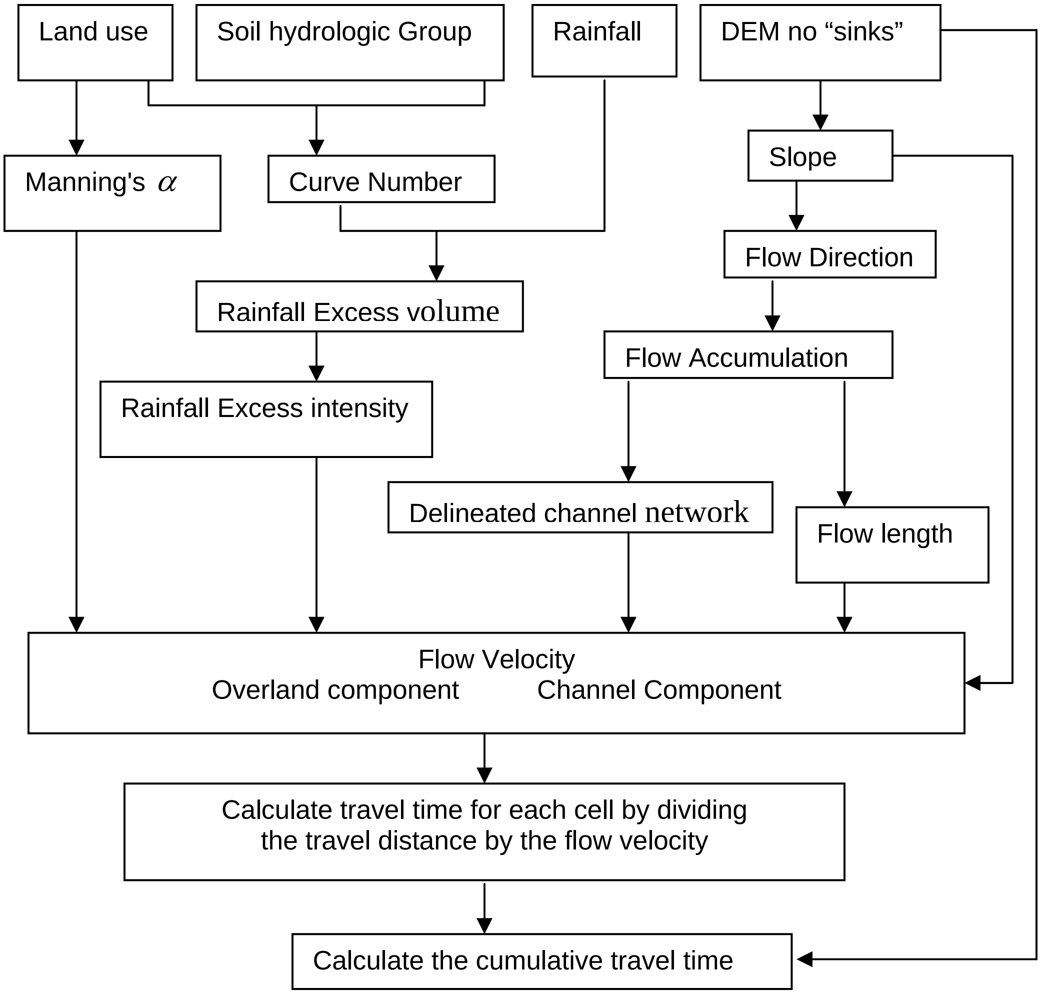

Figure 1. Flow chart for the calculation of the travel time for the sediment particles

Application of Stream Flow Model (SFM)

The basic data layers required to estimate the SDR based on the travel time were a DEM, precipitation, evaporation, land use/ cover and soil data. Other layers were generated from these basic data layers. A physically distributed hydrological model, the Stream Flow Model (SFM) was used to generate these layers in a spatial domain. The SFM was developed using the "C" programming language. The ability to use the avenue script enables modellers to write scripts appropriate to their needs. The user interface for the SFM was developed using the ArcView GIS software. The SFM uses precipitation and evaporation data to add water to the ground water system and to compute overland flow. The SFM graphical user interface (GUI) offers a function for interpolating precipitation and evaporation over an area using station data (point data).

The SFM simulates daily stream flows using two primary input-data files. One input-data file contains parameter values describing the physical characteristics (*basin.txt* file) of the sub-catchment being modelled. Another input-data file (*rain.txt* and *evap.txt* file) contains values for forcing variables describing the daily total precipitation and potential evapotranspiration occurring over the sub-catchments. The data needed to create the input-data files were required in electronic form as GIS files. One of the primary functions of the SFM GUI is the creation of the model input-data files using these GIS files.

Generation of data layers

Digital Elevation Model (DEM)

The model spatial framework, catchment boundaries and stream networks, were determined using the digital elevation model data (DEM). A DEM of 90 x 90 m for this study was acquired from the USGS. The DEM was corrected for the “sinks” and then data set which consisted of sub-catchments delineations and stream networks bearing topological identification numbers, as well as grids of flow direction, flow accumulation, slope, and other variables were determined. The delineated catchment was discretised into 7 several sub-catchments (Figure 2) based on the pour points (outlets) of the delineated stream network. The main mean physical properties for the discretised sub-catchments are summarised in Table 1.

Table1. Main average attributes of the discretised sub-catchments

Basin ID	Soil WHC* (mm)	Soil Depth (cm)	Area (Km^2)	Hlength (m)	Hslope (%)	UpArea (km^2)	Elevation (m)	SCS CN	Max Cover	Manning Coeff.
2	117.178	94.3787	2758	21776.3	1.6912	2757	2143.9	76.4	0	0.065
4	126.942	101.006	821	23002.3	1.9787	820	1897.4	73.3	0	0.045
5	63.8816	102.938	76	5312.6	0.6324	3654	1198	79.8	0	0.025
8	108.168	97.9412	506	34384	1.865	505	1802.5	73.1	0	0.035
10	77.8595	121.901	918	16939.1	0.901	5078	1309.9	76.9	0.00106	0.035
11	112.868	195.415	597	13419.6	0.874	6261	1121	73.9	0.00147	0.075
12	88.6997	150.232	586	18397.8	0.9661	585	1213.9	75.4	0.00106	0.055

*WHC = water holding capacity, Hlength = hillslope length, Hslope = hillslope (m/100m), UpArea = upslope contributing area, SCS = soil conservation service curve number, max cover= maximum % cover of land that is impervious

Land use and land cover

In this research a digital land cover data set for Masinga catchment was clipped from the land use / land cover map of Kenya derived from a twelve-month series of 1-km vegetation index imagery (Loveland and Belward 1997). This was used because there was no available recent data for the Masinga catchment at a finer resolution. The land cover was further classified to reflect the main land use/cover in Masinga catchment. Using the land use/ land cover in conjunction with soil information, rainfall incident on a sub-catchment was partitioned to separate surface runoff from water infiltrating into the soil. The land use/land cover and soils data were also used by the SFM to calculate response function of each sub-catchment. The response function described how excess precipitation was routed to the outlet of the sub-catchments. The response coefficient is one of the factors required for the HSDD model.

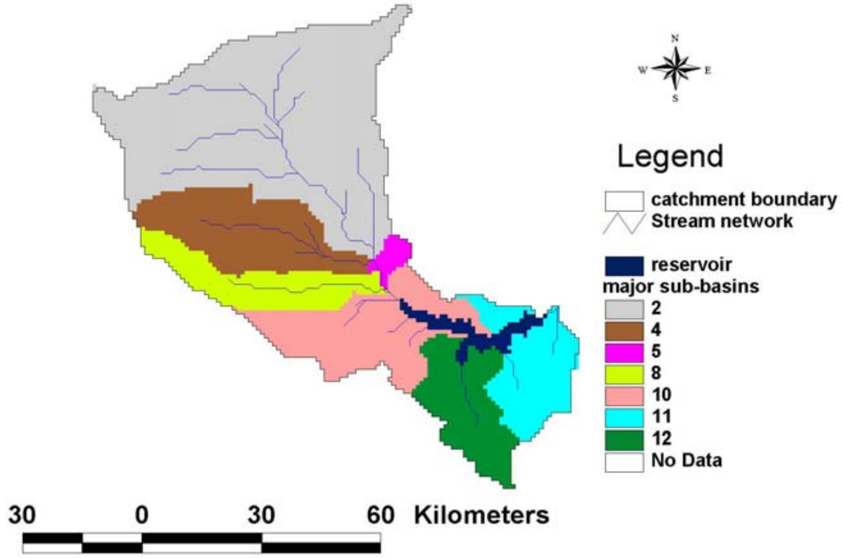

Figure 2. Major sub-catchments of Masinga

Soil data

The SFM requires data describing the average water holding capacity of the soils in centimetres (cm), average hydrologically active soil depth in centimetres (cm), textural description of the soil, average saturation soil hydraulic conductivity in centimetre per hour (cm/hr), average Soil Conservation Service (SCS) curve number for the soils, maximum percentage of the catchment which is impervious, and minimum percentage which is impervious for each sub-catchment that makes up the catchment being modelled.

These data layers were required at fine resolutions, which was not available and hence these parameters were extracted from the Digital Soil Map of Kenya (FAO, 1998) by clipping the data set for the study area. In creating the data set for those attributes missing from the FAO digital soil data set, relationships from existing literature were used.

Determination of the SCS curve number

The model required the curve numbers to estimate the surface runoff. A number of attribute files are required to estimate the curve numbers. Each mapping unit (sub-catchment) within the study area was assigned a record id, the percentage that is excessively drained, somewhat excessively drained, well drained, moderately well drained, imperfectly drained, poorly drained, and very poorly drained. The attribute data file describing the four hydrologic soils groups based on FAO data (Table 2) was used in this study. These data were used to assign each mapping unit to a hydrologic soil type using the relation shown in Table 3. In this study, the spatial SCS curve numbers were determined by merging the hydrologic soil groups and land use/ land cover shape files. The land use/ land cover shape file and its attribute table were loaded into Arc View. The hydrologic soil groups shape file and its associated attribute table were also loaded into ArcView. The ArcView “field calculator” was used to estimate the CN based on relationship between the SCS curve numbers, the four hydrologic soils groups, and land use/ land cover types given in Table 3. The spatial curve number shape file was then converted into a CN grid and was used in the model simulation.

Table 2. Table showing the relation between FAO soils drainage classes and the four hydrologic soil groups used to determine the SCS curve number

Hydrologic soil group	FAO drainage groups
A	Excessively drained Somewhat excessively drained Well drained
B	Moderately well drained
C	Imperfectly drained
D	Poorly drained Very poorly drained

Table 3. The relationship between land cover /hydrologic soil group combinations and runoff curve numbers

Land Cover Description	Hydrologic soil group A	Hydrologic soil group B	Hydrologic soil group C	Hydrologic soil group D
Urban and Built-Up Land	73	82	88	90
Dryland Cropland and Pasture	71	80	86	86
Irrigated Cropland and Pasture	64	74	81	84
Cropland/Grassland Mosaic	63	73	82	87
Cropland/Woodland Mosaic	51	68	78	82
Grassland	60	76	81	89
Shrubland	48	62	73	78
Savanna	44	65	77	82
Deciduous Broadleaf Forest	55	66	74	79
Evergreen Broadleaf Forest	55	66	74	79
Water Bodies	100	100	100	100
Herbaceous Wetland	100	100	100	100
Wooded Wetland	100	100	100	100
Barren or Sparsely Vegetated	75	80	85	90

Rainfall and evaporation data

Daily variations in weather drive the calculation of the stream flow estimates. Fluxes of water between the atmosphere and the Earth’s surface are described using geospatial estimates of precipitation and evaporation. In this study, data from georeferenced weather stations within Masinga catchment (Figure 3) were used. The daily rainfall and evaporation were interpolated using the

Inverse Distance Weighting (IDW) method and the spatial grids were generated into *rain.txt* and *evap.txt* files, a format used by the SFM. The text files were used in the model simulation.

Runoff grid layer

The surface runoff (excess rainfall) was estimated using the SCS curve number method. This was based on the relation given as:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{4}$$

Where Q is the daily runoff (mm), P is the daily rainfall (mm) and S is the estimated retention parameter (mm) estimated using the relation:

$$S = 254\left(\frac{100}{CN} - 1\right) \tag{5}$$

The P, S, Q, and CN were generated on a grid basis and the “Map calculator” in ArcView was used in the calculations.

The flow velocity of the runoff was estimated using the Manning’s equation based on the coefficient of velocity (Equation 6). This was computed using the ArcView’s “Map calculator”. Velocity coefficients for each type of land use/cover type were estimated using values given in Table 4 (after Maidment et al. 1996). The velocity was estimated on a spatial basis (grid basis) and was used in estimating the travel time. The velocity was estimated using the relation:

$$v_i = (\alpha_i \, s_i^{1/2})\, q_i \tag{6}$$

Where v_i is runoff velocity (m/s), s_i is slope of cell i (m/m) and q_i is specific runoff rate (m/s) (i.e. runoff rate per unit cell area).

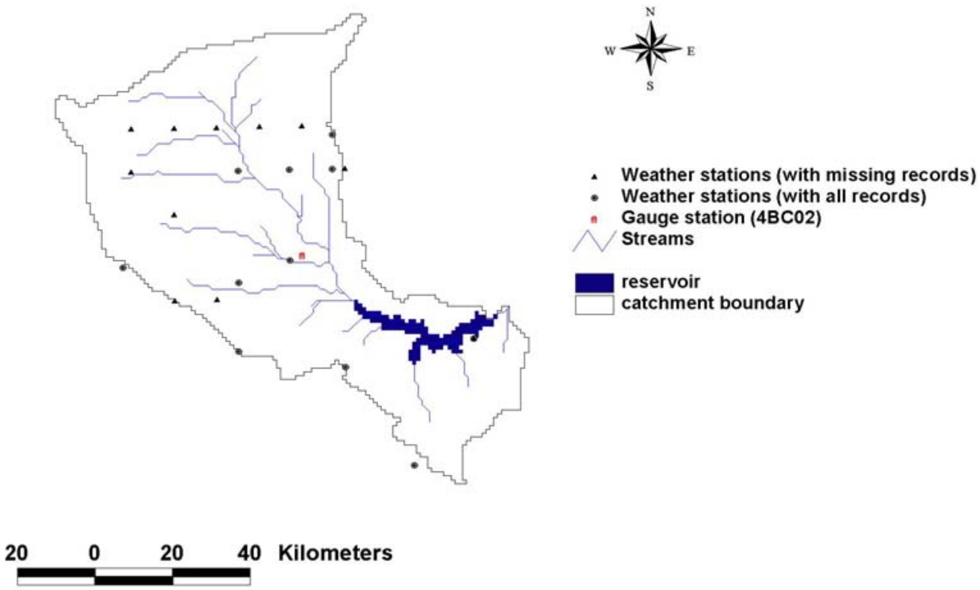

Figure 3. Distribution of weather stations and location of gauging station within Masinga catchment

Table 4. The relationship between land cover description and velocity coefficient

Land Cover Description	Velocity Coefficient
Urban and Built-Up Land	6.3398
Dryland Cropland and Pasture	0.4572
Irrigated Cropland and Pasture	2.7737
Cropland/Grassland Mosaic	0.3962
Cropland/Woodland Mosaic	0.3962
Grassland	0.6401
Shrubland	0.4572
Savanna	0.4267

Model run

After the grids were created, they were generated into texfiles (.txt), a format used in SFM. The most important texfiles were the *basin.txt*, *response.text*, *rain.txt* and *evap.txt*. The SFM GUI has a menu where different functions can be selected. Using the SFM menu, a number of outputs were simulated. Some of the simulated outputs included the daily stream flow, the soil water conditions, and the sub-catchment runoff yields. The travel time, which was the main grid layer, sought for to use in the HSDD model was generated in a spatial domain by overlaying the flow length and velocity grid layers.

Model validation

The SFM was validated using the observed and simulated daily stream flows for 1992 at Tana-Sagana gauging station number 4BC02. The year 1992 was chosen because there were daily rainfall and evaporation records for the whole year for all weather stations considered in this study. The Tana-Sagana gauging station was the only one with all daily stream flow records for 1992. Figure 4 shows the observed and the predicted daily stream flows for the chosen gauging station number 4BC02. Other model outputs such as sub-catchments' soil water conditions and excess sub-catchments' runoff can also be used for model validation. However, these were not used in this study because there are no available measured records for these outputs for long periods.

A statistical criterion for evaluating hydrological goodness of fit between the measured (observed) and the predicted (simulated) values was applied. The results were compared using the Coefficient of model Efficiency (COE) according to Nash-Sutcliffe (1970) given as:

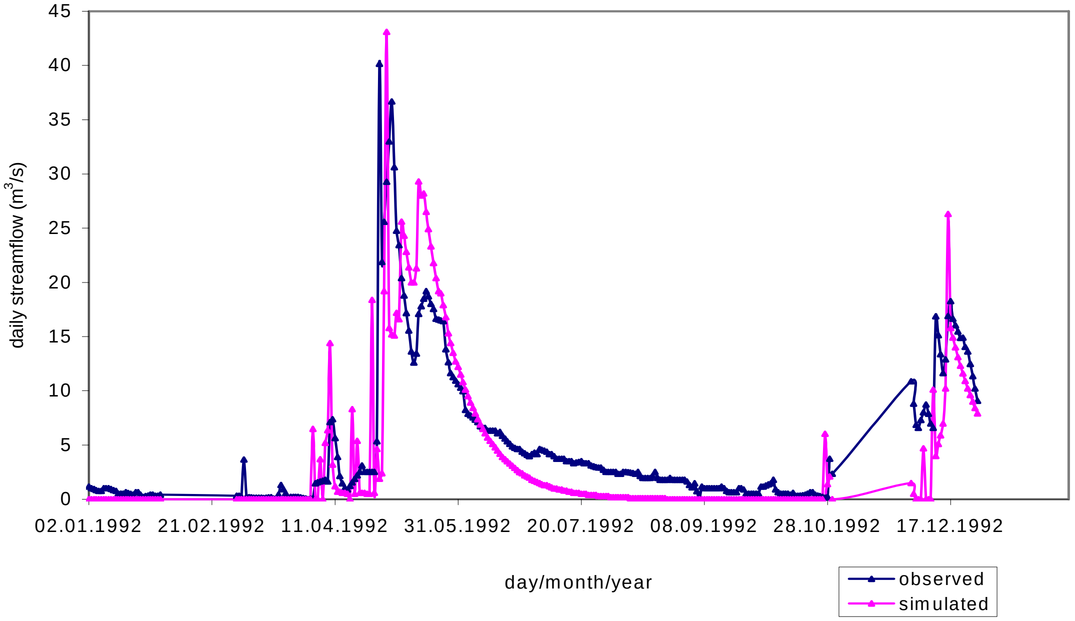

Figure 4. Observed and Simulated daily stream flows at Tana-Sagana gauging station (4BC02) in 1992

$$COE = 1 - \left(\frac{\sum_{i}^{n} (q_i - q_s)^2}{\sum_{i}^{n} (q_i - q_m)^2} \right)$$

(7)

Where *COE* is the coefficient of Efficiency, q_i is the observed (measured) daily stream flow (m^3/s), q_s is the simulated (predicted) daily stream flow (m^3/s), n is the number of observations and q_m is the mean observed daily flow (m^3/s). From the results, a coefficient of efficiency of 0.64 was obtained. The best coefficient value should be about 1.0 and the value of 0.64 shows that the simulated and observed flows have a moderate correlation and hence the model can be relied upon.

Results and Discussion

After determining the travel time of the runoff, the spatial sediment delivery ratio was estimated. Figure 5 shows the spatial SDR for Masinga catchment based on the developed HSDD model. The sediment delivery ratio averaged for all the grid cells for Masinga catchment using the developed approach is 0.29. This was done based on the area-weighted method for each sub-catchment. The sediment delivery ratio value was also calculated at the main outlet of catchment using the drainage-area method suggested by Vanoni (1975) and USDA SCS (1979). The estimated SDR values are 0.158 and 0.21 respectively. The USDA SCS method seems to give an overall value of SDR that compares fairly well with that estimated using the developed approach in this study. However, these are mean values that cannot be used for spatial estimate.

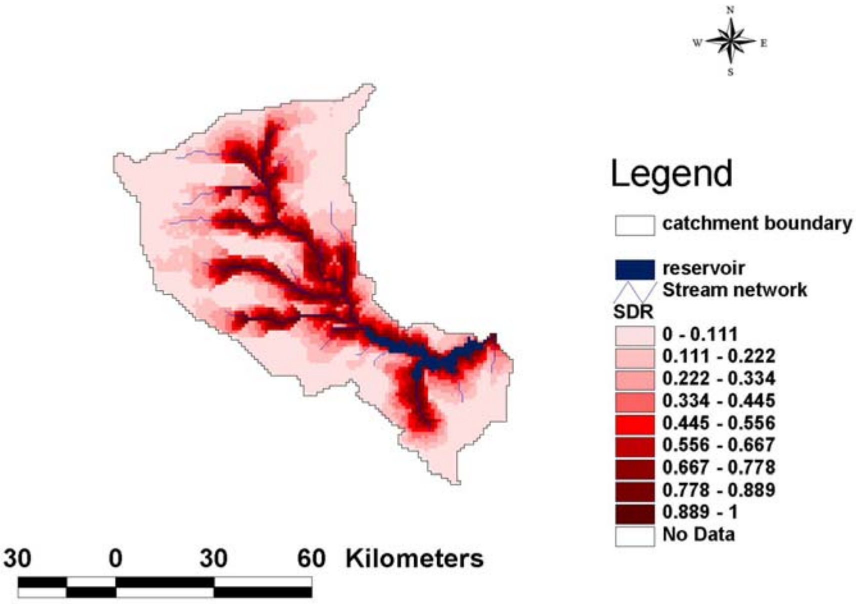

Figure 5. Spatial SDR for Masinga catchment

The sediment delivery ratio values imply the integrated capability of a catchment for storing and transporting the eroded soil. The spatial SDR for this study was determined as a function of the runoff travel time. Results of Figure 5 show that the further away an area is from the stream, the longer the travel time and hence the lower the SDR. The greater the flow velocity along the flow path is, the shorter the travel time and the higher the SDR. It should be emphasised that any two locations that are equidistant from the outlet may not have the same travel time. This means that travel time does not follow concentric zones. Flow velocity in reality is controlled by conditions such as the surface vegetation type and roughness, and elevation changes over the drainage area. In this study, it was established that longer travel time tended to occur in areas with rougher surfaces (vegetated areas) compared with bare and open land surfaces.

The results show the spatial variation of SDR even within the same sub-catchment. This shows how inaccurate the use of the drainage-area SDR method that takes only the area into consideration is. There is also a great variation of the overall SDR at the outlets of the sub-catchments again pointing to the shortcoming of using the mean SDR at the catchment outlet.

The results in this study are based on the model before it was calibrated and it is envisaged that better model performance could be attained if it is calibrated. Some of the parameters that could be adjusted for better model performance include the SCS CN and velocity coefficients. Land use/land cover and the DEM at finer resolutions could improve the model prediction.

Conclusions

The sediment delivery ratio is affected by many highly variable physical characteristics of a catchment. It varies with the drainage area, slope, relief-length ratio, runoff-rainfall factors, land use/land cover and soil properties. Although empirical equations relating SDR with one or more factors are still being used to estimate SDR, their application is limited to only small catchments with adequate data. Furthermore these empirical methods do not consider the spatial variation of the many interacting factors within a catchment. This study has developed a spatially distributed approach that can be used to estimate the spatial sediment delivery for any size of a catchment. The model estimates the SDR on a grid basis. The study provides a useful procedure that can be used in rural catchments were data on sediment measurements for long periods is lacking.

Acknowledgements

The authors are grateful to ÖAD (Austrian Exchange Service) for the financial support to carry out this study.

References

Arnold, J.G., Williams, J.R., Srinivasan, R., and King, K.W. (1996) The Soil and Water Assessment Tool (SWAT) User's Manual. Temple, TX.

Bras, R.L. (1990) Hydrology: An Introduction to Hydrologic Science. Addison-Wesley Publishing Company. Reading, MA.

Dickinson, A., and Collins, R. (1998) Predicting erosion and sediment yield at the catchment scale. In: F.W.T. Penning de Vries, Soil Erosion at Multiple Scales, Principles and Methods for Assessing Causes and Impacts, edited by F. Agus and J. Kerr, 317.Oxon, New York.

FAO. (1998) Soil Map of the World, Revised Legend, FAO World Soil Resources Report No. 60. Food and Agricultural Organisation of the United Nations, Rome, Italy.

Fernandez, C., Wu, J.Q., McCool, D.K., and Stöckle, C.O. (2003) Estimating water erosion and sediment yield with GIS, RUSLE, and SEDD, Journal of Soil and Water Conservation, 58(3), 128-136.

Ferro, V., and Minacapilli, M. (1995) Sediment delivery processes at basin scale. Hydrological Sciences Journal, 40, 703-716.

Ferro, V., and Porto, P. (2000) Sediment Delivery Distributed (SEDD) model, Journal of Hydrologic Engineering, 5(4), 633-647.

Jain, M.K., and Kothyari, U.C. (2000) Estimation of soil erosion and sediment yield using GIS, Hydrological Sciences Journal, 45 (5), 771-786.

Khanbilvardi, R.M., and Rogowski, A.S. (1984) Quantitative evaluation of sediment delivery ratios. Water Resources, Bulletin, 20, 865-874.

Loveland, T. R., and Belward, A. S. (1997) The IGBP-DIS global 1 km land cover data set, Discover: first result, International Journal of Remote Sensing, 18, 3289–3296.

Maidment, D.R., Olivera, J.F., Calver, A., Eatherral, A., and Fraczek, W. (1996) A unit hydrograph derived from a spatially distributed velocity field, Hydrological Processes, 10(6), 831-844.

Maner, S.B. (1958) Factors affecting sediment delivery rates in the Red Hills physiographic area, Transaction of American Geophysics, 39, 669-675.

Nash J.E., and Sutcliffe, J.V. (1970) River flow forecasting through conceptual models - Part I: A discussion of principles, Journal of Hydrology, 10: 282-290.

Novotny, V., and Olem, H. (1994) Water Quality: Prevention, Identification, and Management of Diffuse Pollution. Van Nostrand Reinhold, New York, New York.

Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K., and Yoder, D.C. (1997) Predicting soil loss erosion by water - a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). United States Department of Agriculture, Agricultural Research Service (USDA-ARS) Handbook No. 703. United States Government Printing Office, Washington, DC.

Renfro, G. W. (1975) Use of erosion equations and sediment delivery ratios for predicting sediment yield. In Present and Prospective technology for Predicting Sediment Yields and Sources, Agricultural Resources Services, ARS-S-40, 33-45. US Dept. Agric., Washington, D.C.

Richards, K. (1993) Sediment delivery and drainage network. In: Channel Network Hydrology, edited by K. Beven and M.J. Kirkby, 221-254.

Roehl, J.E. (1962) Sediment source areas, and delivery ratios influencing morphological factors, International Association of Hydrological Sciences, 59, 202-213.

Saenyi, W.W. (2002) Sediment Management in Masinga Reservoir, Kenya. Ph.D. Thesis, University of Agricultural Sciences (Boku), Vienna, Austria.

Sun, G., and McNulty, S. (1998) Modeling soil erosion and transport on forest landscape. Proceedings of 29th International Conference on Erosion Control Association, Reno, Nevada, February 16-20 1988, pp. 187-198. Reno,Nevada.

USDA-SCS. (1979) United States Department of Agriculture - Soil Conservation Service. National Engineering Handbook, Sec. 4. Hydrology.

Vanoni, V.A., (ed). (1975) Sedimentation Engineering. ASCE Manuals and Reports on Engineering Practice No.54. American Society of Civil Engineers, New York.

Walling, D.E. (1983) The sediment delivery problem, Journal of Hydrology 65, 209-37.

Williams, J.R. (1977) Sediment delivery ratios determined with sediment and runoff models. Proceedings Symposium on Erosion and Solid Matter Transport in Inland Water. Int'l. Assoc. Hydrological Sci. No. 122, pp. 168-179.

Williams, J.R., and Brendt, A.D. (1972) Sediment yield computed with the Universal Equation. Proceeding of the American Society of Civil Engineers, 98(HY12), 2087-2098.

Wischmeier, W.H., and Smith, D.D. (1978) Predicting Rainfall Erosion Losses - A guide to Conservation Planning. Agriculture Handbook No. 537, USDA, Washington, D.C.

Yagow, E.R., Shanholtz, V.O., Julian, B.A., and Flagg, J.M. (1988) A water quality module for CAMPS. Paper presented at the International Winter Meeting of the ASAE, Chicago, Illinois, December 13-16 1988. Chicago, Illinois.