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Full Length Research Paper

Coupling agricultural non-point source (AgNPS) model and geographic information system (GIS) tools to predict peak runoff and sediment generation in the upper River Njoro catchment in Kenya

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Human interference in the upper River Njoro catchment has led to the increased exposure of the land to accelerated erosion. An application that combined the capabilities of remote sensing, geographic information system (GIS) and agricultural non-point source (AgNPS) model was used to estimate peak runoff rate and sediment yield from the upper River Njoro catchment. Remotely sensed Landsat Thematic Mapper (TM) images were used to obtain land cover and associated AgNPS model input parameters. Other input parameters for the model were extracted from GIS layers using the agricultural non-point source-integrated land and water information system (AgNPS-ILWIS) interface. Surface water quantity and quality data including peak runoff and sediment yield of selected storm events were obtained from two gauging stations, within the catchment. Base flow separation was done so that measured direct peak runoff rate and sediment yield generated by direct runoff could be determined and compared directly with the model simulated results. Simulated peak runoff rates in Upstream (Treetop) station were satisfactory with an EFF of 0.78 and a percent error of 4.1%. The sediment yield was also reasonably estimated with an EFF of 0.88 and a 2% error. The downstream (Egerton) station results were also satisfactorily predicted with peak runoff rate having an EFF of 0.69 and a 5.5% error of estimates, while the estimated sediment yield had an EFF of 0.86 and a 2.5% error.

Key words: Peak runoff, sediment, agricultural non-point source (AgNPS), geographic information system (GIS), integrated land and water information system (ILWIS), soil loss.

INTRODUCTION

Soil erosion and sedimentation are major environmental problems which cause degradation of natural resources in river basins. Such degradation may be in the form of reduction of land productivity due to loss of fertile soil from agriculturally productive land and undesirable deposition of eroded material in the lower reaches of the river channels increasing frequency of floods and depletion of ground water resources. Sediment deposits also cause accumulation of silts in lakes or reservoirs reducing their useful life. Fertilizer chemicals are transported into water bodies together with sediments causing excessive growth of water plants, which result in clogging of water courses, loss of aquatic life and other related problems. Scouring of river channels has also been noted to destroy hydraulic structures along the river courses.

The destruction of soil through erosion is becoming of particular concern because soil formation is an extremely slow process. Serious soil erosion is occurring in Kenya's major agricultural regions and the problem is growing as more land is brought under agricultural production. Surface runoff is a critical variable in determining the rate of soil erosion and sediment transport. Its turbulence is known to be an influential factor in detachment of soil by

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overland flow. The rapid growth in the world population, which leads to the need for more crops, will only intensify the water problem, particularly if soil erosion is not contained.

The River Njoro catchment is part of the larger Lake Nakuru catchment, and one of the rivers originating from the Eastern Mau forest of the Mau Complex and draining into the saline Lake Nakuru. The River Njoro catchment is a high potential area and is under intensive cultivation. The forested hill slopes of the catchment have undergone extensive deforestation, which has led to increased soil erosion, low recharge and remarkable fluctuation in stream flows. Through erosion, the fertile topsoil and the sediment generated are transported by the stream and get deposited in the lower reaches in the river and the Lake. Lake Nakuru is a protected area for biodiversity conservation. As a habitat for various flora and fauna, its degeneration in quantity and quality has adverse effects on biodiversity which it supports.

Recent advancements in computer technology have provided new techniques to study and tackle environmental problems for effective and efficient environmental systems management. It is now easier to analyze and process enormous amount of data within a very short time. The computer has become a versatile tool for studying and modeling our environment. In addition, since the early 1970’s, satellites have scanned the earth and furnished digital images of several wavelengths ranging from the visible part of the spectrum to the middle infra red (De Jong and Riezebos, 1992). Developments in the field of erosion studies have led to the design of new models that can handle large number of parameters and perform large number of calculations. These models are often linked to geographical information system (GIS) thus simplifying the modeling task.

In the present study, the integrated land and water information system (ILWIS) developed by International Institute for Aerospace Survey and Earth Sciences ITC (Meijerink et al., 1988) was used in a GIS-Model link to determine and handle the distributed input and output of the agricultural non-point source (AgNPS) pollution model. The distributed model was used to predict sediment yield and runoff for single storm events. A large depth of literature on AgNPS model exists as expounded on by Finn et al. (2006). GIS capabilities in incorporating catchment data through remote sensing and spatial analysis with hydrological data have been shown to be effective in determining peak flows at various points along a stream channel (Onyando et al., 2005).

Study area

The River Njoro catchment is located approximately 150 km North West of Nairobi, Kenya. The catchment is part of the larger Lake Nakuru catchment. The area of the catchment is approximately 250 km^2 and varies in altitude from 2700 m above mean sea level (a. m. s. l.) on the eastern side of the Mau complex, one of Kenya’s major water towers to 1700 m a. m. s. l at the outlet in Lake Nakuru. The mean annual precipitation is 1200 mm distributed bimodally with peaks in May and October. The study focused on the upper catchment which is approximately 127 Km^2; it is shown in Figure 1, which also includes drainage network and the sampling sites at Treetop and Egerton River gauging stations.

The Egerton gauging station is located at (00.37347°S, 35.94077°E) with an altitude of 2203 m a. m. s. l while treetop gauging station located at 3.7 km upstream of Egerton station has coordinates of (00.37528°S, 35.92029°E) and altitude of 2285 m a.m.s.l. The geology and soils of the area is influenced by the volcanic nature of the Rift valley. The upper part of the catchment is predominantly loamy soils that developed from ashes and other pyroclastic rocks of recent volcanoes (Ralph and Helmidt, 1984), whereas the lower catchment is covered by erosive lucustrine soils.

MATERIALS AND METHODS

Rainfall, stream flow and water quality

The rainfall data used in the study were taken from the readings of non-recording rain gauges of the Egerton University weather station (00°23’S, 35°55’E) at 2238 m a. m. s. l within the sub-catchment. Eleven storm events were considered in the study. The corresponding stream flow was also taken at the two monitoring sites selected for the study. Stream flow measurements were made by recording the height of the surface of water read from a staff gauge after the storms. The elevation readings were then converted to discharge using a rating equation.

Runoff sampling was also done at the two monitoring sites after storm events for sediment concentration analysis in the laboratory. A depth integrating hand sampler was lowered into the stream at a constant vertical speed, and also raised to the surface at a constant speed. Three traverses were made across the stream section to come up with the suspended sediment load for the section. The samples were then filtered, oven dried and weighed. Using the direct runoff volume, the weight of the sediment was converted into a sediment yield in tonnes for a particular storm.

Agricultural non-point source (AgNPS) model simulations

The process of predicting the required outputs via the model-GIS link was divided into three phases.

Spatial database preparation

The AgNPS model requires a large volume of data from various sources. The basic input data into the GIS were contours, drainage network, boundary and land cover maps. The contour, drainage and boundary maps were created by vectorization from topographic maps of the study area, whereas the land cover map was processed from a Landsat TM image of 2001 by multi spectral image processing capabilities of the ILWIS software. It was assumed that there were no major changes in land use that occurred between the year 2001 and 2005 when the data collection was done. Three spectral bands, bands 3, 5 and 7 were used in the

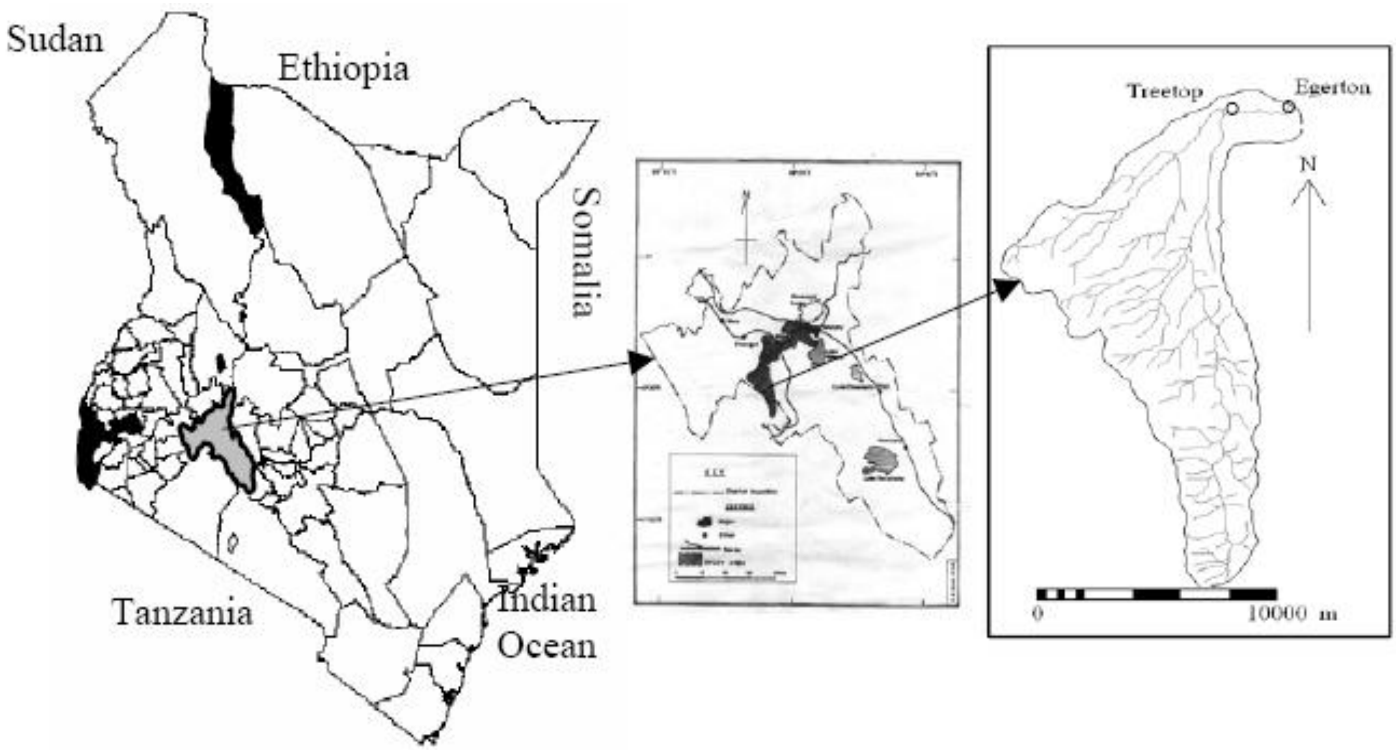

Figure 1. Map showing Kenya, River Njoro catchment in Nakuru District and Upper catchment with drainage network and gauging stations at Treetop and Egerton,

supervised classification using Gaussian maximum likelihood classifier method to extract thematic information from the satellite imagery. The other parameters required by the model were either derived from the basic input maps or input as constants.

Derivation of spatial layers

This phase utilized the capabilities of GIS to come up with other spatial layers related to the basic input layers. The contour, drainage and boundary maps were rasterized (converted to raster maps) and used to generate the digital elevation model (DEM) which was later used to generate dependent raster layers of cell number, slope length, slope shape, flow direction, channel indicator and channel gradient. The land cover map was used to derive USLEs' K (soil erodibility), C (Cropping), and P (Conservation Practice) factors, SCS-CN (Soil Conservation Service-Curve Number), SCC (Surface Condition Constants), COD (Chemical Oxygen Demand) and Manning's coefficient maps as shown in Figure 2. The values of these parameters for the study area were determined and are presented in the Table 1.

The C (crop management) factor values, which compares the ratio of soil loss under a given crop to that of bare soil for the study area were found to range from 0.038 to 0.35 from literature (Crops C-factor manual). The forest cover had a lower value of C indicating good protection to the soil as compared to the shrub land, settlement and agriculture. A high C-factor has the effect of reducing infiltration during a storm, resulting to an increase in surface runoff and sediment concentration in the runoff.

Another parameter for the model is the chemical oxygen demand (COD) which is a measure of oxygen required to oxidize organic and oxidizable inorganic compounds in water, is an indicator of the degree of pollution and varies with land cover. AgNPS assumes soluble COD. COD estimates in runoff is based on average concentration of COD in runoff, and allowed to decay with time once they enter a channel according to an exponential decay. The values of this parameter for the various land cover ranged from 20 to 170. The COD factor was found to increase in the order of forests, settlement, shrubs and agriculture, implying that agricultural land required more oxygen to oxidize organic and oxidizable inorganic compounds in runoff.

Soil erodibility factor (K) is a soil dependent parameter. It is a function of the percentage of silt and coarse sand, soil structure, permeability of soil and the percentage organic matter. Based on soil Nomographs by Morgan (1986), the K-factors for the various land covers were found to be in the range 0.035 to 0.29. Another parameter, the soils manning coefficients refers to the soils roughness and thus implies the resistance of flow of water in and on the soils. Therefore it is one of the important parameters for describing water flow over the ground. Lower values of this coefficient denote less resistance to flow and vice versa. Foster et al. (1981) estimated the average Manning's coefficient values for different land uses, and based on their tabulated values, the spatial distribution of the coefficient for the various land covers in the study area was derived.

The curve number (CN) is a dimensionless index that describes runoff as a range between 1 and 100, with 100 indicating maximum runoff. It is dependent on the hydrological soil cover complex of the catchment. This cover complex comprises of a combination of the hydrologic soil group and land use and treatment class. Curve Number values were assigned to each complex to indicate their specific runoff potential. The curve number values for the catchment ranged from 25 to 90 based on literature by Chow et al. (1988). The greater the curve number, the greater the surface

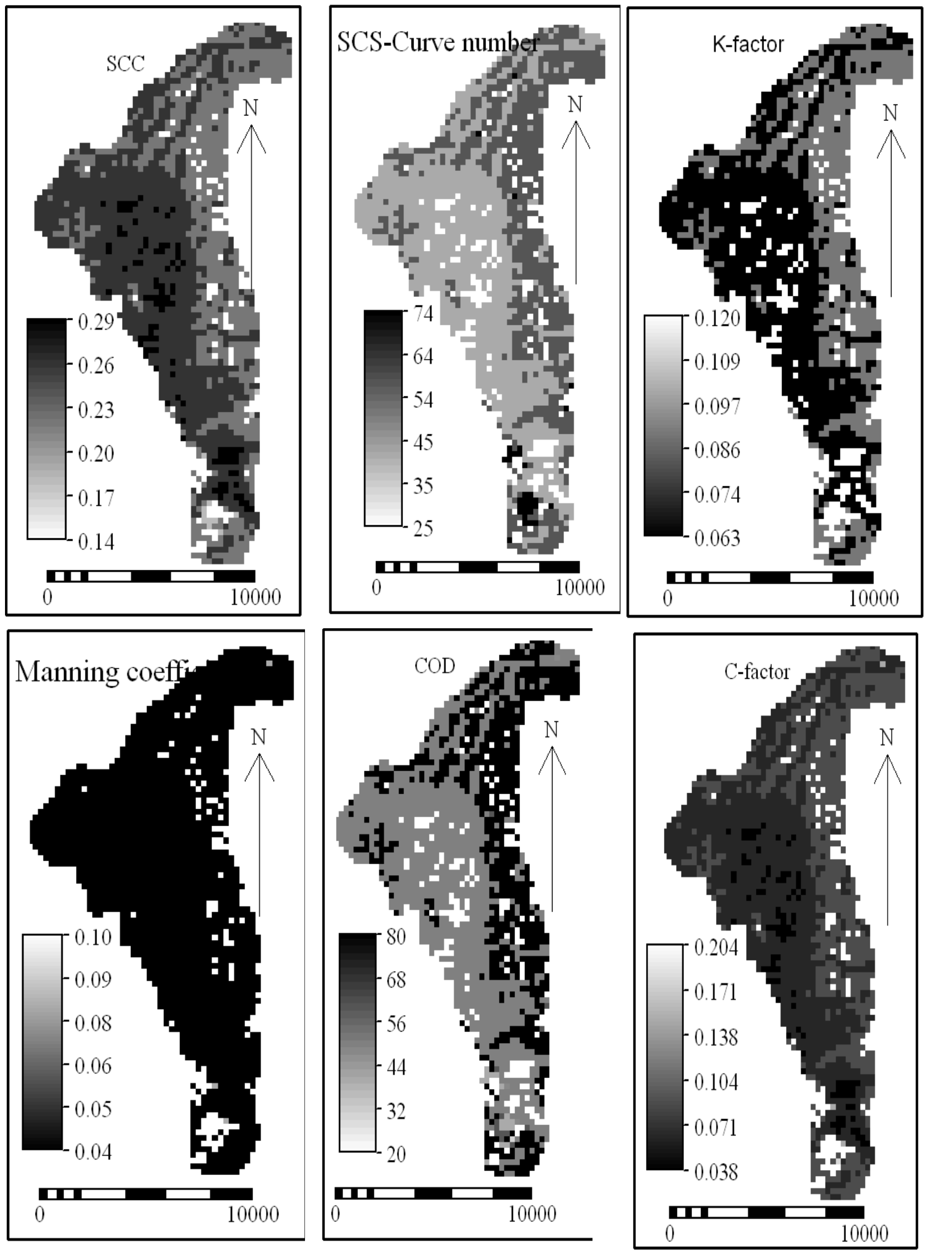

Figure 2. Spatial distribution of land use related parameters.

runoff volume.

Geographic information system (GIS) and model interface

This phase involved the coupling of the interface GIS with the model. An extraction program was used to extract data from the GIS environment and transform and take it to the model. An interface program (GRIPs) developed by ITC-Water Resources and Environmental Studies (WRES) was used to convert ILWIS map files, containing the parameter data, to an input data file acceptable by the model. This program reads the map values for the respective cells and converts them to AgNPS data format.

The input data was then entered in the interface and checked for flow routing, by eliminating sink holes and ensuring that the catchment drains through the outlet. The GRIPs then run the model and creates ILWIS files which contain the model outputs to be compared with the observed outputs.

RESULTS

Peak runoff rates

The simulated peak runoff rates generated by the model are presented in Table 2 together with the observed ones.

Table 1. Land use and its related variables.

Parameter	SCC	SCS	COD-factor	K-factor	C-factor	Manning coefficient
Forest	0.29	25	20	0.035	0.038	0.04
Agriculture	0.29	78	170	0.290	0.350	0.04
Shrubs	0.22	58	80	0.090	0.087	0.04
Settlement	0.14	90	37	0.150	0.320	0.15

Table 2. Peak runoff rate (m^3/s) results.

Event	Rainfall (mm)	Treetop			Egerton		
		Observed	Simulated	Error (%)	Observed	Simulated	Error (%)
15/01/04	40.6	2.966	3.065	-3.3	2.547	2.622	-2.9
11/04/04	42.5	2.981	3.088	-3.6	2.534	2.603	-2.7
23/05/04	45.0	3.055	3.179	-4.1	2.714	2.876	-6.0
22/07/04	37.0	2.267	2.406	-6.1	2.018	2.160	-7.0
11/08/04	28.0	2.843	2.692	5.3	2.543	2.321	8.7
14/11/04	8.4	2.522	2.406	4.6	2.192	2.019	7.9
23/11/04	9.5	2.747	2.617	4.7	2.349	2.191	6.7
25/11/04	17.5	2.521	2.670	-5.9	2.253	2.369	-5.2
16/12/04	25.6	2.910	2.882	1.0	2.887	2.790	3.4
26/01/05	16.5	2.468	2.521	-2.2	2.239	2.352	-5.1
22/03/05	26.5	2.863	2.747	4.1	2.469	2.358	4.5

Sediment yield

The simulations of sediment yield by the same model are presented in Table 4. In the same Table, observed sediment yield is presented for comparison of the level of the accuracy of the simulations.

DISCUSSION

Peak runoff rates

The results presented in Table 2 showed the model to have satisfactorily predicted the peak runoff rates in both the stations. On an individual basis all the storm events were predicted with a percent error ranging between 1 and 8.7. Events 22/07/04 and 11/08/04 were the most poorly predicted in the two stations with percent error values of -7.04 and 8.7 (Treetop) and -6.1 and 5.3 (Egerton) respectively. However, the gross errors in peak flow rates estimation represented an overestimate of only 0.139 (Treetop) and 0.142 m^3/s (Egerton) for event 22/07/04 and an underestimate of only 0.15 (Treetop) and 0.222 m^3/s (Egerton) for event 11/08/04, this could be due to fact that these two were complex storms with rainfall following an irregular pattern. The event of 16/12/04 was the best predicted. An error of 3.4% (Treetop) and 1% (Egerton) was produced for this simulation. The results were subjected to statistical analysis by comparing the observed and predicted output data for individual storm events at the two monitoring stations.

The goodness of fit between the predicted and observed peak runoff rates was assessed for the stations. For the upstream station the average percentage error between observed and predicted values was 4.1%. This agreement is confirmed by satisfactory EFF values of 0.78. For Egerton station, there is generally a good correlation between the observed and predicted peak runoff rates. The average percent error between observed and predicted values was 5.5%, and EFF value of 0.69 as shown in Table 3.

The proximity of the EFF to 1 and scatter smaller percentage errors is an indication of good predictive ability of the model as far as peak runoff rate is concerned. The statistics presented above were found to be consistent with those for similar work involving AgNPS done in other parts of the world. Khoelliker and Humbert (1989) in their work in northeast Kansas found a percent error of 3%, Young et al. (1987) in an agricultural catchment in Minnesota had a 1.6% error in their estimations and a correlation coefficient of 0.81. Lee and White (1992) also found a good agreement between observed and simulated data for runoff. Suttles et al. (1999) simulation of runoff rate in Georgia coastal plain had an EFF of 0.85, whereas Mostaghini et al. (1997)

Table 3. Statistical parameters of observed and predicted Peak runoff rate.

Catchment	Area (km^2)	No. of events	Peak runoff rate	
			Efficiency	Error (%)
Egerton	127	11	0.69	5.5
Treetop	110	11	0.78	4.1

Table 4. Sediment Yield (Tonnes) results.

Event	Rainfall (mm)	Treetop			Egerton		
		Observed	Simulated	Error (%)	Observed	Simulated	Error (%)
15/01/04	40.6	326.12	331.51	-1.7	276.21	282.21	-2.2
11/04/04	42.5	335.45	327.62	2.3	288.43	283.33	1.8
23/05/04	45.0	340.66	336.62	1.2	279.57	286.77	-2.6
22/07/04	37.0	290.22	295.14	-1.7	239.38	248.73	-3.9
11/08/04	28.0	331.98	325.44	2.0	264.14	270.06	-2.2
14/11/04	8.4	288.14	295.55	-2.6	239.37	246.72	-3.1
23/11/04	9.5	290.64	296.89	-2.2	241.36	247.14	-2.4
25/11/04	17.5	295.84	306.26	-3.5	266.35	258.34	3.0
16/12/04	25.6	318.88	324.83	-1.9	281.30	275.71	2.0
26/01/05	16.5	307.23	303.34	1.3	248.42	243.51	2.0
22/03/05	26.5	312.00	306.73	1.7	266.11	259.63	2.4

simulation of runoff was nearly 100% of the observed. In Hesse, central Germany 3.8% was the error found for runoff simulations.

Sediment yield

Only a fraction of the sediment eroded within a catchment finds its way to the outlet as sediment yield. Large storms were generally seen to result in high sediment yield as shown in Table 4. As is the case of runoff, the sediment yield was also satisfactorily predicted. The individual percent error values for the various rainfall-runoff events ranged between 1.2 and 3.9. Sediment results presented in Table 4 indicate that Event 25/11/04 was the worst predicted for the two stations, with an error of -3.5% for the Treetop station and 3.0% for Egerton station. The best predicted event was that of 26/01/05, which had an error of 1.3 and 2.0% for Treetop and Egerton stations respectively. The difference in errors between the best and worst sediment yield predictions was found to be small, in addition the errors for sediment yield were lower than those for the runoff results. This could be due to the fact that, all particles were allowed to participate in the channel scouring, and not the AgNPS default that allows only sand particles to erode. The study area also falls in the tropics where storms are intense. The choice of storm type influences the energy-intensity value, and hence the erosive potential of a storm. Four AgNPS storm types exist according to AgNPS model classification of storms, these are 1a, 1, 2 and 3 in increasing amount of the energy intensity-values. The lower percent errors in the sediment yield results were realized when storm type 2 is used in the simulations. This type of storm is normally common in tropical environments and has a high potential to erode due to its high intensity. The storm type and channel scouring assumptions were deemed valid in this work because of the resulting increase in the accuracy of predictions upon their use. This argument has also been confirmed by Perrone and Madramootoo (1999) when using AgNPS for watershed modeling in Quebec. They used storm type 1 which was appropriate for Quebec conditions. The sediment yield results were then subjected to further statistical analysis to establish the model efficiency and the average percentage error for the predictions.

As in the case of peak runoff rates, the goodness of fit between the predicted and observed sediment yield was assessed for each of the two stations separately. For the upstream station the average percentage error between observed and predicted values was 2.0% with a satisfactory EFF value of 0.88. For Egerton station, there was also a good correlation between the observed and predicted sediment yields. The average percent error between observed and predicted values was 2.5% while for the model efficiency, an EFF value of 0.86 was obtained as summarized in Table 5.

The results obtained in the study compared favourably

Table 5. Statistical parameters of observed and predicted sediment yield.

Catchment	Area (km^2)	No. of events	Sediment yield	
			Efficiency	Error (%)
Egerton	127	11	0.86	2.5
Treetop	110	11	0.88	2.0

to works using AgNPS by Young et al. (1987), which over predicted sediment yield by 2.5% and had an EFF of 0.95 in the Trevor watershed. In Hesse, central Germany, there was a 5% error in sediment estimation. Walling et al (2003) compared the performance of AgNPS and ANSWERS models coupled to GIS in estimating sediment concentration and found the two models to be reasonably consistent with the recorded values, although the AgNPS model appeared to provide closer agreement between observed and simulated values.

Conclusion

Deterioration of surface water quality and quantity is a problem in the River Njoro catchment. In the present study the peak runoff rate and sediment yield from the upper River Njoro catchment was predicted using a combination of Remote sensing and AgNPS model in a GIS environment. The GIS platform provided a faster and better method for spatial modeling and availed output maps that are easy to understand.

The stream flow is an integrating measure of all the hydrological processes operating within the catchment. Most catchments in the developing countries are not gauged with the appropriate instruments for runoff measurement. However, AgNPS, a storm event based model can be used to predict the runoff and sediment yields based on the rainfall information and land use and its related parameters which can be derived in a GIS environment using Remote sensing information. The combination of AgNPS, GIS and Remote Sensing has shown to be a useful substitute to the *in situ* measurement of runoff and sediment yield based on the results realized in the study.

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REFERENCES

Chow VT, Maidment DR, Mays LW (1988). Applied Hydrology. McGraw-Hill, Singapore.

De Jong SM, Riezebos HTH (1992). Assessment of erosion risks using Multispectral Remote Sensing Data and an empirical erosion model. Proc. 3rd Euro. Conf. GIS (EGIS'92). 23-27th April, Munich. pp. 895.

Finn MP, Usery EL, Scheidt DJ, Jaromack GM, Krupinski TD (2006). An interface between the Agricultural Non-Point Source (AGNPS) pollution model and the ERDAS Imagine Geographic Information System (GIS). Int. Assoc. Chin. Professionals Geogr. Inf. Sci. (CPGIS) 12(1):9-19.

Foster GR, Lane LJ, Nowlin JD, Laflen JM, Young RA (1981). Estimating erosion and sediment yield on field sized areas. Trans. ASAE 24(50).

ILWIS 3.1. (2001). User guide. ITC Enschede, The Netherlands

Khoelliker JK, Humbert CE (1989). Applicability of AGNPS model for water quality planning. ASAE, St. Joseph, MI.

Lee MT, White DC (1992). Application of GIS databases and water quality modelling for agricultural non point source pollution control. Research Report 014. Water Resource Center, University of Illinois Urbana-Campaign, Urbana, IL. pp. 24.

Meijerink AMJ, Valenzuela CR, Stewart A (1988). The Integrated Land and Water Information System (ILWIS). Scientific Status Report on the project Geo-information System for land use zoning and watershed management. ITC Pub. No. 7. International Institute of Aerospace Survey Earth Science (ITC). The Netherlands pp. 115.

Morgan RPC (1986). Soil Erosion and Conservation. Longman. Hong Kong.

Mostaghini SS, Park W, Cooke RA, Wang SY (1997). Assessment of management alternatives on a small agricultural watershed. Water Res. 31(8).

Onyando JO, Musila F, Awer M (2005). The use of GIS and Remote sensing techniques to analyse water balance of Lake Bogoria under limited data conditions. J. Civ. Eng. Res. Pract. 2:1.

Perrone J, Madramootoo CA (1999). Sediment yield prediction using AGNPS. J. Soil Water Conserv. 54(1).

Ralph J, Helmidt S (1984). Agricultural Management Handbook. Ministry of Agriculture and Livestock Development, Nairobi, Kenya. p. 397.

Suttles JB, Vellidas G, Bosch DD, Lowrance R, Sheridan JM, Usery EL (1999). Watershed scale simulation of sediment and nutrient loads in Geogia Coastal plain stream using the Annualized AGNPS model. ASAE Paper 40(5).

Walling DE, He Q, Whelan PA (2003). Using 137Cs measurements to validate the application of the AGNPS and ANSWERS erosion and sediment yield models in two small Devon catchments. Soil Till. Res. 69(1/2).

Young RA, Onstad CA, Bosch DD, Anderson WP (1987). AgNPS: Agricultural Non point source pollution model. A Watershed analysis tool. USDA, Conserv. Res. Rep. No. 35.