Journal of Civil Engineering Research and Practice, Vol. 7 No.1, April 2010, pp. 61 - 76

Application of GIS-Based Spatially Distributed Hydrologic Model in Integrated Watershed Management: A Case Study of Nzoia Basin, Kenya

[1]Nyadawa, M.O., [2]Karanja, F. and [2]Njoroge, T.

[1]Dept. of Civil, Construction and Environmental Engineering, Jomo Kenyatta University of Agriculture and Technology. monyadawa@yahoo.com

[2]Dept. of Geospatial and Space Technology, University of Nairobi

ABSTRACT

The overall objective of this study was to study the impact of change of land use / land cover on catchment runoff response using FEWS-Flood Model as the rainfall-runoff conversion model in Nzoia basin, Kenya. Land use / land cover grid data were processed for the years 1986 and 2000 in IDRISI Kilimanjaro environment while both soil data and necessary meteorological data inputs were processed in necessary formats in ArcView. The study revealed that loss of forest cover between the year 1986 and 2000 equaled gain in acreage under cropland land/ woodland mosaic in the same period. Analysis of impact of change of land use/ land cover between 1986 and 2000 also revealed increased peaks in resulting hydrographs as a result of increased acreage under crops and reduced forest cover for same storm characteristics. This has given a rationale to recent increased flood disaster in the basin.

Key Words: *Nzoia, Integrated watershed management, USGS SFM, land use, land cover*

1.0 INTRODUCTION

1.1 Background of study

Kenyan watersheds are increasingly being degraded and suffer both flood or drought related hazards depending on the geographical location of the watershed (NEMA, 2004). And this trend has made adoption of integrated watershed management strategy become a national priority through the new water act (GoK, 1999, 2002). Most urgent now is need for tools to facilitate extensive quantitative hydrologic analysis for assessment of water balance of various basins to form a basis for policy actions and by extension strategic rules of integrated watershed management. In this regard, modelling hydrologic cycle at a local scale still remain the most important scientific method of research for water balance assessment of basins. A model is defined as a mathematical or physical system obeying certain specified conditions, whose behavior is used to understand a physical, biological, or social system to which it is analogous in some way (Linsley, 1981). Many authors have written on historical development of rainfall-runoff modelling and challenges encountered (e.g. Linsley, 1981 and Todini, 1988). These authors noted that: 18^{th} century was the era of empirical equations whose solutions could easily be computed manually, 19^{th} century was the era of computer assisted lumped modelling in hydrology and 20^{th} century is the multi-dimensional hydrologic modelling approach. The state-of-the-art in the 20^{th} century is close to reality but, time consuming in terms of computational capacity of computers and data acquisition. In reality, hydrological processes are perceived as being nonlinear and stochastically variable in both space and time (Keith, 1991). However, most physically-based distributed models capture only nonlinearity by partial differential equations describing surface and subsurface flow processes. To obtain a procedural model with realistic boundary conditions, these equations must usually be solved by approximate numerical methods, with state variables predicted at grid of points in space and time. This leads to the problem of interpolation if observed data are point observations.

The advent of GIS and remotely sensed data has given a new dimension to procedural steps in spatial distributed hydrologic modelling. Apart from flexibility in visual displays, GIS is capable of creating continuous data layers from point observation and combining the same with other grided datasets. Two major GIS-based hydrologic models which have extensive global applications are Soil and Water Assessment Tool-SWAT (Neitsch et al., 2002) and, Famine Early Warning System Flood Model-FEWS Flood Model (Guleid et al.,2000). FEWS- Flood Model also referred to as Geospatial Stream Flow Model (Geo-SFM) is a semi-distributed hydrologic model being promoted by U.S. Geological Survey (USGS). The model has been applied by USGS for flood forecasting in a number of African countries including Mozambique (Limpopo basin), Ethiopia (Awash basin), Somali (Shebelle basin), Kenya(Tana, Nzoia, Nyando basins). Because of lack of adequate observed datasets at basin scale, the applications were based on course satellite meteorological datasets, the details can be found in USGS website (http:/earlywarning.usgs.gov/)

Nzoia basin is chosen for this study as a typical example of a flood disaster prone basin which is now a government pilot basin for integrated watershed management approach for flood management through Western Kenya Community-Driven – Development and Flood Mitigation Project (ADCL, 2006). The basin will require many catchment management decision support tools and more reliable flood forecasting methods. A number of studies (JICA, 1987; JICA, 1992; APFM, 2004a; Hussein et al, 2005; ADCL, 2006) have been carried out in Nzoia basin with a view to providing flood damage mitigation solutions, but effective structural and non structural mitigation measures are yet to be realized. The study by Hussein et al. (2005), whose overall objective was to develop an integrated flood early warning system based on satellite and ground observed data for Nzoia River basin, applied Geo-SFM in development of flood risk maps for the flood plain. It was observed in the study that 30m DEM data produced accurate inundation maps, which were linked with model forecast river levels for flood early warning purposes. Mild, moderate and severe flood scenarios were generated and linked to settlements, schools and other livelihood zones data. The results were comprehensive information for flood contingency planning, preparedness and response in Nzoia. The flood warning initiatives is part of the mandate of Western Kenya

Community-Driven –Development and Flood Mitigation Project. However, catchment management options can be analyzed on the basis of historic data and therefore, the focus of this study.

Now the focus is the ongoing Western Kenya Community-Driven –Development and Flood Mitigation Project (ADCL, 2006) which emphasizes community participation in the planning and the management processes to ensure democratic governance of this catchment will require tested decision support tools for the initiative to come up with a comprehensive integrated watershed management strategies and Flood Early Warning System. The study presented here is meant to assess the suitability of Geo-SFM in integrated watershed management, particularly monitoring land use / land cover changes on river flow regime. The results will automatically add value to the on going community flood management initiative in Nzoia basin in terms understanding of the effects of land use change on runoff and planning future meteorologic data network. For example, clarification of linkage between catchment runoff response and change in land use / land cover will contribute partly to understanding the cause of failures of Earth dykes in the lower of River Nzoia, and therefore, help in developing sustainable catchment management strategies for the basin.

The overall objective of this study is to study the impact of change of land use / land cover on catchment runoff response using FEWS-Flood Model as the rainfall-runoff conversion model in Nzoia basin.

Specific objectives are:

i. To process and display remotely sensed land use / land cover datasets at chosen time intervals for Nzoia River basin.
ii. To demonstrate the effect of change in land use/ land cover in river flow regime using FEWS-Flood Model .

1.2 General description of the study area

Geographical location of Nzoia is indicated in Fig.1. Nzoia basin is situated between latitudes 1^0 30’N and 0^0 05’S and between longitudes 34^0E and 35^0 45’E and is the largest basin in Kenya’s Lake Victoria basin with an approximate area of 12,709km^2 and a length of 334km up to its outfall into the lake. Nzoia system has its sources in the forested highlands (Mt. Elgon, Cherangani hills, Nandi Hills and Kakamega forest). River Nzoia experiences perennial flooding in its lower reaches especially the Budalangi area of Busia district. Additional information of the river morphology of the river system is given by APFM(2004a).

Throughout the year in Lake Victoria Basin there is no distinctive dry season, but there are two maxima, one in April and the other in October. The highest rainfall occurs in the northwestern parts, where Nzoia basin is located, and gradually reduces in the southeastern parts. Though figures vary with small margins depending on different authors, JICA (1987) states that mean annual rainfall in Nzoia basin is 1360mm with average annual runoff of 82.7m^3/s at gauging station near the outfall to lake(1EE01).

Unique ecosystems within the basin are flood plain at the river delta, Kakamega forest in the middle zone and Mt. Elgon, Cherangani hills and Nandi hills in the upper zones. Land use range from smallholder subsistence farms to large scale farming/plantations.

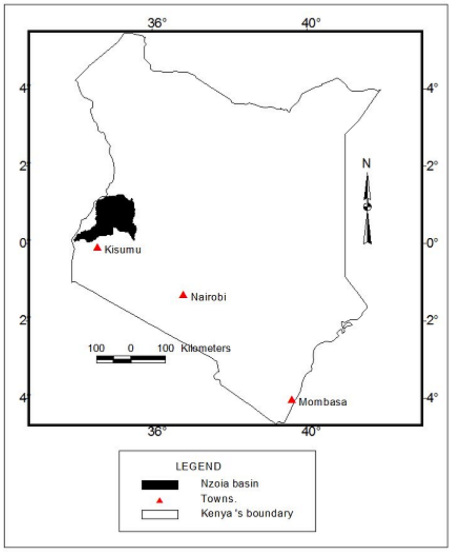


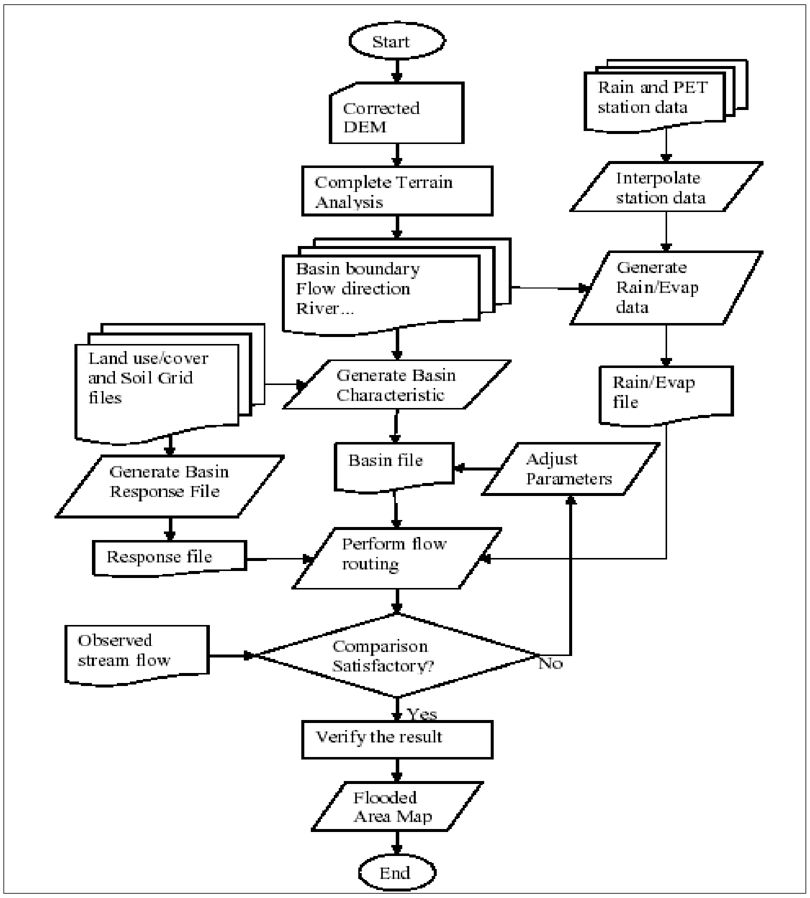
Fig. 1 Geographical location of Nzoia basin in Kenya

1.3 Model Overview

The background of model development is well documented in GeoSFM Users Manual (Debbie 2006). GeoSFM, also referred to as FEWS Flood Model was developed by scientists at the USGS Center for EROS in Sioux Falls, South Dakota, US. FEWS Flood Model requires six types of datasets for its operation are:

- Rainfall (Observed or RFE)
- Observed discharges (QPE)
- Potential evaporation (PET)
- Soil data (Soil)
- Land use/ land cover (LU/LC)
- Digital Elevation Model data (DEM)

Detailed model operation are schematically illustrated in Fig. 2. Fundamental hydrologic equations are Water balance, Runoff Curve Number method and Muskingum channel routing method.



Source: Behailu (2004)

Fig. 2 Operation layout of USGS SFM model

2 DATA AND METHODS

Input datasets were categorized into four groups: meteorological / hydrological, soil data, land use / land cover, and topographical datasets. Meteorological data range is given in Table 1 and other grid themes are shown Fig. 3 to8.

Daily rainfall observations between the year 1979 and 2000 for seventeen stations distributed over basin were collected from Meteorological Department, Nairobi for this study. Table 1 shows rainfall station codes (station id), geographical position (longitude and latitude) and years whose data were acquired for this study. Black shades in Table 1 indicate missing data ranges, these gaps resulted in discontinuities in data series for the corresponding station. Rainfall stations with data discontinuity in a particular year are omitted when creating interpolated continuous rainfall surface for that year. The range of data used for model calibration is indicated in the last row of the table as 1979 to 1984. Fig. 4.3 shows geographical distribution of meteorological stations indicated in Table 1.

Table 1 Rainfall and discharge data used in this study and their continuity status

sno	Station id	Station name	Long. (deg.)	Lat. (deg.)	1979	1980	1981	1982	1983	1984	1986	2000
1	8834098	Kitale	34.983	1.000		■						
2	8934013	Mumias girls	34.500	0.333							■	■
3	8934016	Lugari	34.900	0.667		■				■		
4	8934040	Butere	34.500	0.217						■		
5	8934078	Kaimosi	34.950	0.217						■		■
6	8934096	Kakamega	34.767	0.283			■					
7	8934098	Kimilili	34.683	0.867								■
8	8934119	Webuye	34.767	0.617	■				■			
9	8934127	Ukwali D.O.	34.200	0.200		■	■	■			■	■
10	8934133	Mumias sugar	34.500	0.367	■	■					■	■
11	8934139	Bunyala	34.050	0.083								
12	8934183	Nzoia sugar	34.500	0.533	■	■				■	■	■
13	8934189	Yala	34.533	0.100	■	■	■	■	■			
14	8935112	Nandi forest	35.067	0.200	■					■	■	■
15	8935117	Kipkabus	35.517	0.317	■					■		■
16	8935172	Burnt forest	35.417	0.200	■	■	■	■	■	■		■
17	8935181	Eldoret met	35.283	0.533	■		■					
18	1EE01	Nzoia RGS	34.226	0.178							■	■
					CALIBRATION DATA RANGE							

Key

■ Missing data

□ Complete data

Observed daily discharges were acquired from Department of Water and Irrigation for station code 1EE01. See Table 4.1 and Fig.4.3 for geographical coordinates and location respectively. The station was considered a better control section for all rainfall input upstream**.** The station has continuous data between 1963 and 1984, after which discontinuities characterize data series. However, six years of daily record ranging from 1979 and 1984 was considered sufficient for calibration.

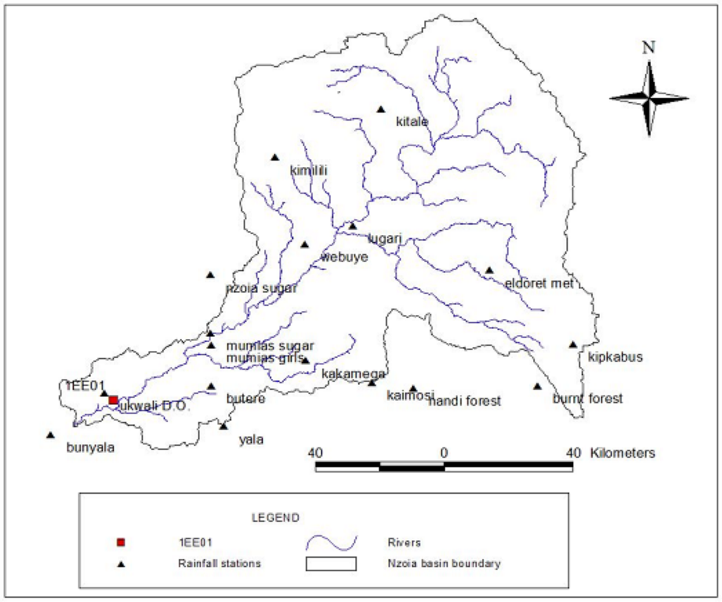


Fig. 3 Distribution of rainfall and discharge stations used in this study

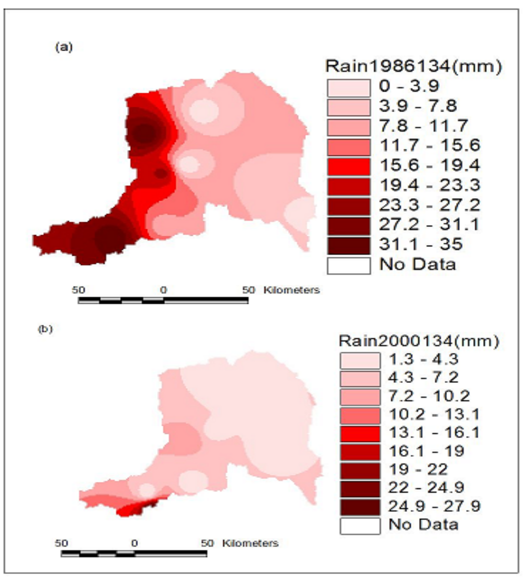
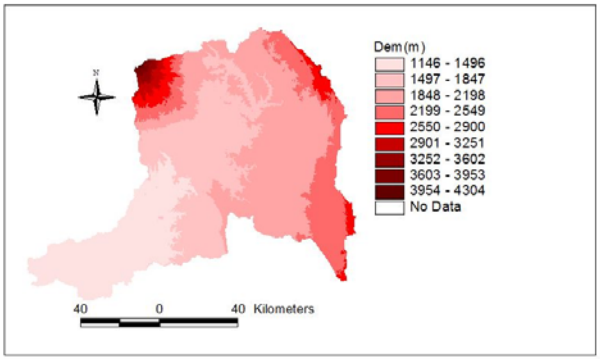


Fig. 4 Sample of daily rainfall grid from point measurement locations shown in Fig. 3 (a) Interpolated rainfall surface for day 134 of 1986 and (b) day 134 of 2000



Source: FAO (2004)

Fig. 5 DEM used in the study

Digital Elevation Model (DEM) data used in this study was sourced from FAO (2004) (see Fig. 5).

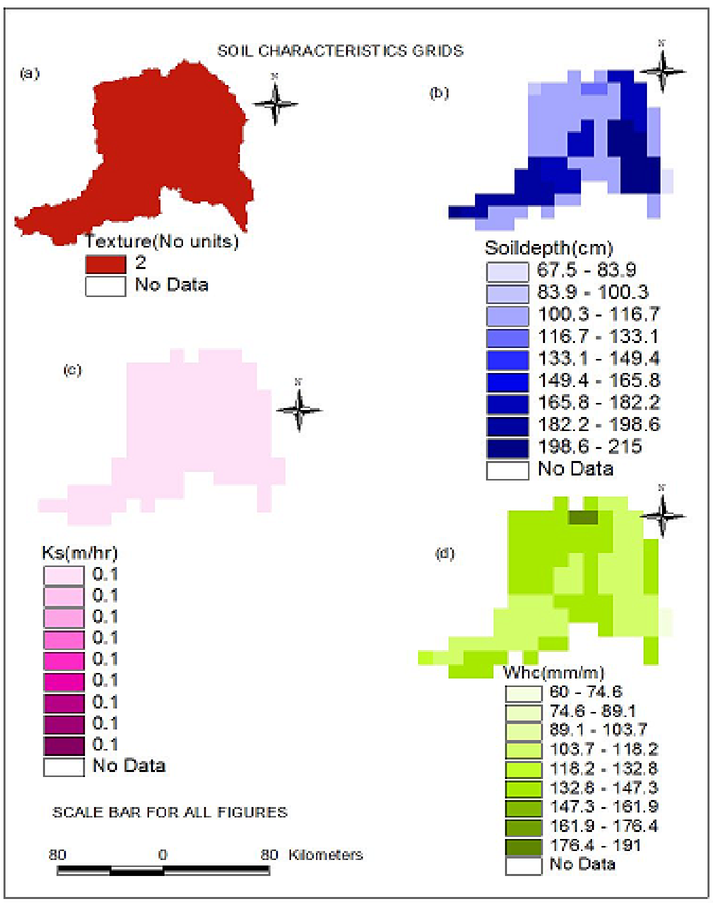


Fig. 6 USGS soil parameters {(a) texture-non dimensionless (b) soil depth-cm (c) Ks – m/hr and (d) Whc –mm/m}

The other input data for FEWS Flood Model are: average water holding capacity of the soils in millimeters per meter, average hydrologic active soil depth in centimeters, textural description, and average saturation soil hydraulic conductivity in meters per hour for each sub-watershed that makes up the watershed being modeled. These data were acquired at USGS Kenya office and clipped for Nzoia basin as shown in Fig. 6.

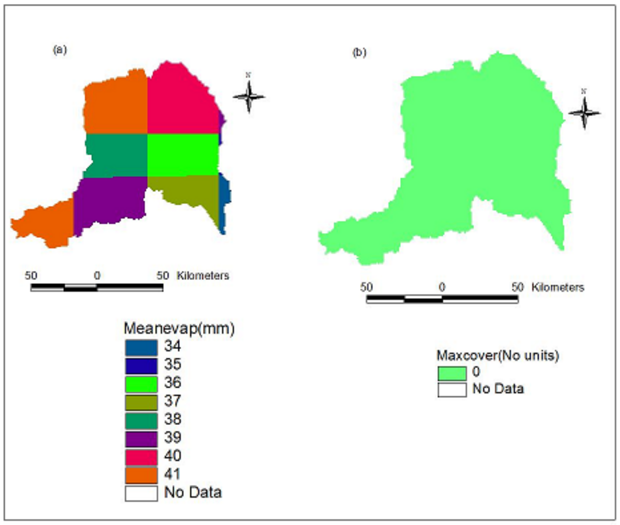
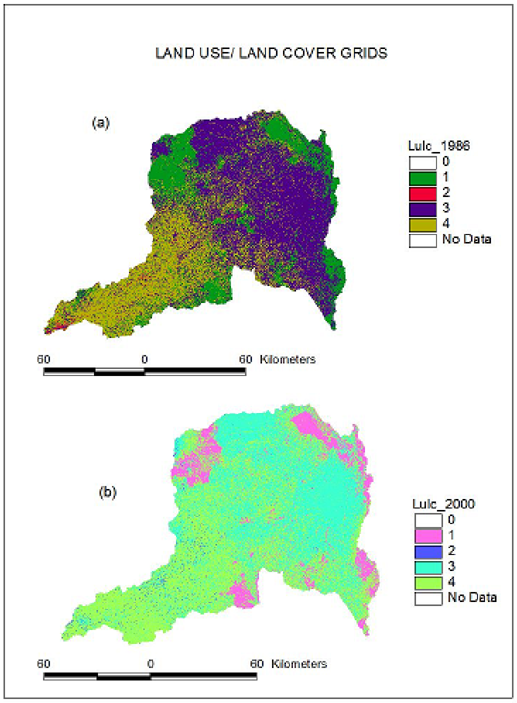


Fig. 8 Evaporation and water cover as used for all computations in this study

(a)Daily mean evaporation(mm) (b) and maximum water cover(dimensionless)

Because of lack of optimum evaporation observation data network in the basin, daily estimates of Potential Evapotranspiration were approximated by mean values from satellite values archived in USGS website (http://earlywarning.usgs.gov/adds). In this case mean evaporation from 1995 to 2003 was used to derive the mean values. Figure 8(a) shows the grid theme for this data. Figure 8(b) shows spatial distribution of maximum impervious cover grid referred to as maxcover grid which is also necessary input into the model. This variable assumes two values: one for water and zero for other conditions. The data are available for download at USGS Global Land Cover Characteristics database (http://edcdaac.usgs.gov/glcc/af_int.html). In this case the maxcover value is assumed as zero (see Fig. 8b).

3.0 RESULTS



Note: For decoding values in legends see Column 1 and 2 in Table 3

Fig. 7 Classification of Land use/ land cover from Landsat images of (a)1986 and (b)2000

Table 2 Characteristics of images used in the study

Type of sensor	period	Bands available	Scene	Spatial resolution
Landsat TM	January March October (1986)	1-5 and 7	P169r59 P169r60 P170r59 P170r60	30m
Landsat ETM	January (2000)	1-5 and 7	P169r59 P169r60 P170r59 P170r60	30m

Land use/ land cover data were based on Landsat scenes of 1986 and 2000 as identified in Table 2. It was assumed that the time interval between the two datasets is long enough to reveal hydrologically significant change. Classification was done in IDRISI KILIMANJARO environment. The images were classified into four major land covers (forest, shrubland, farmland and water) which were considered significant in the study area.

Table 3 Results of image classification

Value	Land cover type (USGS description)	USGS Lu/lc - Code	Pixel count		Area (km^2)		Change in area (km^2)
			1986	2000	1986	2000	
0	Unclassified	0	16341382	2213026	13273	17975	Ignore
1	Evergreen deciduous broadleaf forest	421	3713810	1779710	3016	1445	-1571
2	Waterbodies	500	80399	146103	65	118	ponding
3	Shrubland	321	7332518	6661084	5956	5410	-546
4	Cropland/woodland mosaic	290	4597251	7137715	3734	5798	+2064

Note: Minus sign in change in area column means decrease from 1986 area and plus is vice versa.

Results for image classification are shown in Fig. 7 and Table 3. Due to low spatial resolution of Landsat images used in this study, only four land cover types were identified. These land cover types are identified by legend value numbers as 1, 2, 3 and 4 in Fig. 7(a) and Fig. 7(b) and descriptive meanings are given in column 8 of Table 3. Value column as indicated in Table 3 are just signature identifiers, whereas USGS Lu/lc code and Land cover type columns are available in Debbie (2006) and response coefficients in Guleid et al. (2000)

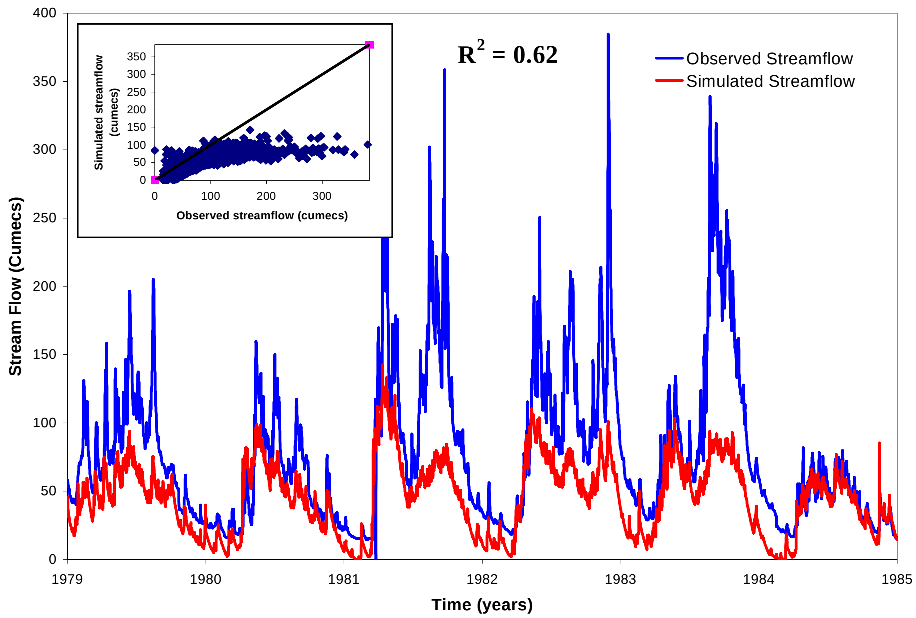


Fig 9 Results of model calibration at 1EE01

Fig. 9 shows results of model calibration. For calibration purposes, continuous series of rainfall data in (Table 1) were terminated at 1984 to correspond to available continuous observed discharge data at 1EE01. Rainfall data for the year 1986 and 2000 were conveniently chosen to correspond to satellite images.

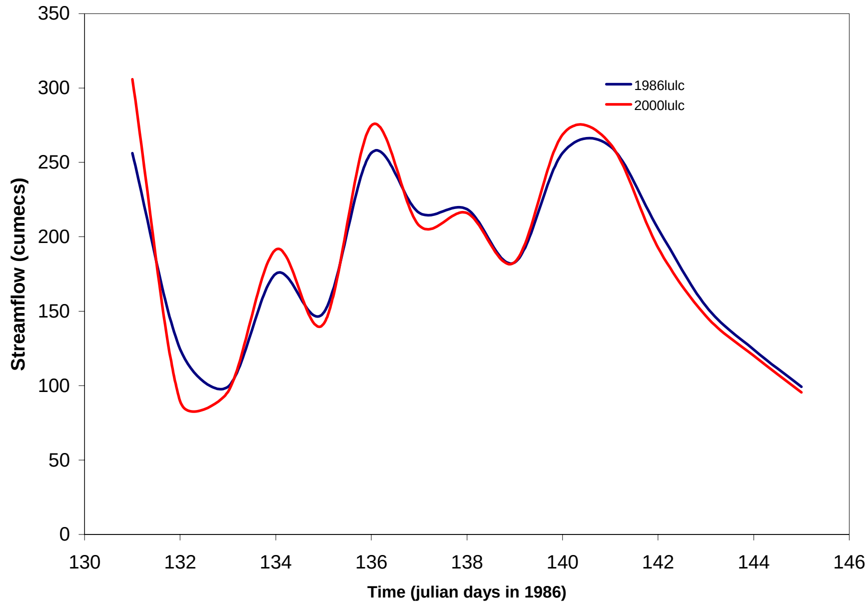


Fig. 10 Demonstration of effect of land use / land cover change on basin runoff response

Table 4 Change of river flow response with change in land use/ land cover data

Sample rains (day 131 to day 142, 1986)	Magnitude of rain (mm) sampled at grid code 72	Simulated streamflow based on 1986lulc data at grid code 72 (m^3/s)	Simulated streamflow based on 2000lulc data at grid code 72 (m^3/s)	Running discharge quantity indices
131	6	256.2408*	305.8508*	-
132	3	124.6012*	89.58248*	-
133	17	99.24273	95.83065	0.965619
134	25	175.0812	191.3512	1.092928
135	7	148.8758	141.3141	0.949208
136	14	256.354	274.7296	1.071681
137	5	216.1633	207.6019	0.960394
138	18	218.5774	215.9146	0.987818
139	6	182.6708	182.9166	1.001345
140	12	256.3077	268.6831	1.048283
141	4	260.7119	262.4284	1.006584
142	6	205.5685	192.7365	0.937578
143		153.4269	146.7103	0.956223
144		124.1015	119.9988	0.966941
145		99.24171	95.45869	0.961881
Totals	123mm	2396.323 m^3/s	2395.674m^3/s	Mean=0.992806

Note: Numbers marked by asterisks have been ignored in summation due to initial model moisture adjustment errors.

Runoff factor (f) given by the ratio of runoff depth (r) to rainfall depth (p) as shown in equation 1 was computed on the basis of data in Table 4.

$$f = \frac{r}{p} \text{ -------------------(1)}$$

In this case p is 123mm and r is averagely 2396 m^3/s which is equivalent to 16mm runoff depth, considering a catchment area of 12709km^2 and hydrograph base time of 13 days.

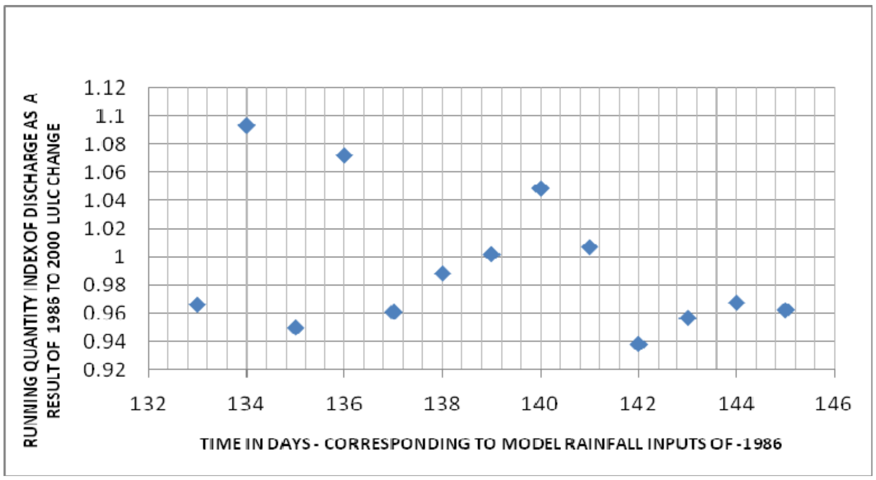


Fig. 11 Simulated results of running discharge quantity indices due to impact of Landuse/Land cover (LULC) change on catchment

4.0 DISCUSSION

Computations of change of area for various classes of land cover from Landsat images of 1986 and 2000 as indicated Table 4 indicate that total loss of forest cover and shrub (1571 plus 5467km^2) is nearly equal to gain in area of cropland land/ woodland mosaic (2064km^2). This finding suggest that farming may be a major cause of deforestation.

Fig. 9 shows results of model calibration. It is evident that the simulated hydrograph matched the trend of the observed during low flows but exhibited large departures during high flows or rainy seasons. Parameter adjustments could only result in a coefficient of determination (R^2) of 0.62. Coefficient of determination equals one for a perfect case where simulated values equal observed or all data fall on the 45^0 inclined line shown in the correlation graph. These results though not very good, were used to generate basin parameters on which the model was used to demonstrate the effect of change in land use on basin runoff response. The reason for poor predictability by the model at high flows could be attributed to inaccuracies in interpolated rainfall due to poorly distributed observation network. Because the correlation is good at low flows it is reasonable to say that raingauge positions which ranged from 9 to 14 in Table1 are not dense enough to capture accurately the extents of spatial variation of rainfall in the whole basin.

Demonstration of the effect of change in land use / land cover data on river flow time distribution was done by keeping all other datasets in the model constant and varying only land use / land cover (Lulc) data. The stability of the model computation was ensured by maintaining values of calibrated parameters. Fig. 10 shows the results obtained when sample rainfall data of twelve days starting day 131 to 142 of 1986 was subjected to land use / land cover data of 1986 and 2000. This period was chosen because it coincided with 1986 image date and most important the data exhibited continuous rainfall which is important for quick runoff response in the model. The basic question to be answered by this computation is “Would rainfall which fell some years back cause more damage if it reoccurred in later years if there are changes in area of similar land uses ?”. It is evident from the resulting hydrographs (Fig. 10) that change in land use / land cover data (Lulc data) affect shape of hydrograph. In this case, reduced forest cover as in 2000 Lulc data increases hydrograph peaks and encourages flooding. Further computation of runoff volumes under simulated hydrographs are shown in Table 4. The computation showed that there is no significant runoff volume change but there is a change in runoff time distribution. The ratio of runoff to rainfall in this case is low (approximately 0.13). This can be summarized that recent increased incidences of flood disasters in the basin is not only due to random occurrences of extreme large storms but also due to effect of change of land use on basin runoff response. It is worth noting that the shape of the two graphs in Fig. 10 is similar. This is expected as the rainfall pattern and magnitude are similar in the two cases leaving any cause of shift to change in area of different classes land use / land cover. The two simulated hydrographs in Fig. 10 are not compared to observed flows due missing records, however, model parameters are maintained from calibration stage. Because rainfall events are maintained for the two land use / land cover scenarios comparison of simulated streamflow curve for year 2000 would be irrelevant for answering the question posed here.

More insight to the effect of change of land use/ land cover on catchment runoff response was done by computation of running discharge quantity indices using 1986 discharges as the base data as shown in Fig. 11. It is evident from Fig. 11 that effect of land use / land cover change on catchment runoff discharge is more pronounced as magnitudes of discharges increases (see indices above 1 and their corresponding rainfall intensity in Table 4). This means that difference of runoff retention effect between forested surface and cropland surface is not significant at low rainfall values. Disturbed surface soils of cropland tend to induce increased infiltration but only at low intensity rainfall.

5.0 CONCLUSIONS

The results of this study are summarized as follows:

i. Computations of change of area for various classes of land cover from Landsat images of 1986 and 2000 indicated that total loss of forest cover and shrub between this period is nearly equal to gain in area of cropland land/ woodland mosaic in the same period. This means that analysis of land use / land cover has revealed that the direction of change is from forest or shrubland to farmland.

ii. Analysis of impact of change of land use/ land cover between 1986 and 2000 revealed increased peaks in resulting hydrographs as a result of increased acreage under crops and reduced forest cover for same storm characteristics. Increased runoff peaks are evident for high intensity rainfall compared low intensity values.

REFERENCES

1. ADCL (2006), " Western Kenya Community – Driven –Development and Flood Mitigation Project", *Inception Report on upper Nzoia and Yala Catchment Management Sub-component,* Appropriate Development Consultants Limited, Kenya.
2. APFM (Associated Program on Flood Management) (2004a). "Strategy for flood management for Lake Victoria basin", Kenya". *Ministry of Water Management and Development, Kenya*.
3. Behailu, S. (2004), " Streamflow Simulation for the Upper Awash Basin", *M.Sc. Thesis*, School of Graduate Studies. Addis Ababa University.
4. Debbie Entenman (2006), "Geo SFM Users Manual Version 1.0", *Center for Earth Resources Observation and Sciences (EROS).* USA.
5. FAO (2004), "Shuttle Radar Topographic Mission (SRTM) Technical Guide", *Department of Geography, University of Maryland*.
6. GoK(1999), "Environmental Management and Co-ordination Act, 1999", *Government of Kenya.*
7. GoK(2002), "Kenya Gazette Supplement Acts 2002, The Water Act 2002", *Government of Kenya.*
8. Guleid Artan, Kwabena Asante, James Verdin and James L. Kiesler, Jr (2000)," Use and Description of the Famine Early Warning System Flood Model", *U.S Geological Survey.*
9. Hussein Gadain, Wilbur Ottichilo, Shem Kifugo, Byron Anangwe, Flavian Mwenga and Vincent Mtaroni (2005), "Flood Early Warning System for Nzoia Basin- Western Kenya: Greater Horn of Africa Flood Mitigation Activities. *U. S. Agency for International Development (USAID), Office of Foreign Disaster Assistance.*
10. JICA (1987), "The study of integrated regional development master plan for the Lake Basin Development Area", *Final Report Vol. 5, Sectoral report 3, Lake Bain Development Authority*, Government of Kenya.
11. JICA (1992), "The study on the national master water plan, sectoral reports", *Ministry of water development*, Government of Kenya.
12. Keith Beven (1991), "Spatially distributed modelling: Conceptual Approach to Runoff Prediction in Recent Advances in David S. Bowles and P. Enda O'Connel (Editor)", *Kluwer Academic Publishers, pp.373-387.* London.
13. Linsley, K. Ray (1981), " Rainfall-Runoff Models- An Overview in Singh,V.P (Editor)", *Proc. of the International Symposium on Rainfall-Runoff Modelling*, Mississipi State University U.S.,Water Resources Publications.

14. NEMA (2004), "State of Environment Report, Kenya: Landuse and Environment", *National Envirinment Management Authority*, Kenya.
15. Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R. and King, K.W. (2002), "Soil and Water Assessment Tool- Theoretical Documentation, Version 2000", *Blackland Research Center*. Texas Agricultural Experiment Station. USA.
16. Todini, E. (1988), "Rainfall-Runoff Modelling- Past, Present and Future", Journal of *Applied Hydrology*, 100, pp. 341-352.