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IMPACTS OF LAND COVER CHANGE SCENARIOS ON STORM RUNOFF GENERATION: A BASIS FOR MANAGEMENT OF THE NYANDO BASIN, KENYA

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ABSTRACT

The effects of conceptual land cover change scenarios on the generation of storm runoffs were evaluated in the Nyando Basin. The spatial scenarios represented alternatives that vary between full deforestation and reforestation. Synthetic storm events of depths 40, 60 and 80 mm were formulated according to the rainfall patterns and assumed to have durations corresponding to the runoff times of concentration. The Natural Resource Conservation Service–Curve Number model was used to generate runoff volumes within the sub-catchments, which were subsequently routed downstream to obtain effects in the whole basin. The simulated land cover change impacts were evaluated relative to values obtained from the actual land cover state of the basin in the year 2000. From the results, an agricultural land cover scenario constituting of about 86 per cent of agriculture indicated increased runoff volumes in the entire basin by about 12 per cent. An agricultural-forested land cover scenario with 40 and 51 per cent of forest and agriculture respectively revealed reduced runoff volumes by about 12 per cent. Alternatively, a scenario depicting a largely forested land cover state with about 78 per cent of forests reduced the runoff volumes by about 25 per cent according to the model estimates. Runoff volumes in the basin were also likely to reduce by about 15 per cent if the appropriate land cover scenario for the respective sub-catchments were to be assumed for runoff management purposes. Considering the prevalent data uncertainty, the study effectively highlights the potential hydrological vulnerability of the basin. The results obtained can form a basis for appropriate catchment management of the area.

KEY WORDS: land cover change; conceptual scenario; hydrological model; synthetic storm; runoff event; Nyando Basin; catchment management; Kenya

INTRODUCTION

Anthropogenic induced land cover changes associated with deforestation to create room for subsistence agriculture are common in developing countries. An evaluation of such changes, their relationships and interactions within the immediate and vulnerable ecosystems is vital to aid decision making geared towards the development of proper catchment management strategies (Corey *et al*., 2007; Baldyga *et al*., 2007). In the recent past, the Government of Kenya through the Ministry of Agriculture and Rural Development[1] in collaboration with the World Agroforestry Centre[2] (ICRAF) and other concerned stakeholders initiated the TransVic project.[3] The aim of the initiative was to develop appropriate land management strategies within the susceptible Trans-boundary Lake Victoria Drainage Basin (LVDB) (Republic of Kenya, 2002; Swallow *et al*., 2003; ICRAF, 2006). A widespread problem identified in the region was the vast land cover degradation within the riparian upstream catchments important in the sustainability of the existing water resources. The Nyando River Basin (NRB) with its headwaters in the endangered Mau Forest Complex (MFC) region in particular was seen to epitomize the degradation because of its physical susceptibility, coupled with the existence of poor land and water management strategies (Krhoda, 1988; Olang *et al*., 2011). Previous studies of the NRB involving change detection from time-series Landsat satellite images have revealed varying proportions of spatio-temporal changes. The headwater sub-catchments exhibited significant depletion of forests due to the need for agricultural expansion and economic sustenance by the rural communities.

The lower parts of the basin, however, exhibited subtle land cover fluctuations that varied between agriculture and grasslands on seasonal basis. From the land cover conversion patterns, it is concluded the basin was more likely to be converted into an agricultural area in the near future if the land cover change trends continued unabated (Rambaldi

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[2]Formerly known as the International Centre for Research in Agro-Forestry.
[3]http://www.worldagroforestry.org/water/transvic.asp

et al., 2007; Olang *et al*., 2011). Further research studies using hydrological models have also revealed the changing response of the Nyando basin, particularly during storm events of the long rainy season (LRS) (Opere and Okello, 2011; Olang and Fürst, 2011). However, with increasing human population in the area and hence continued degradation, it is becoming critical to understand the potential response of the area as a basis for future planning and restoration efforts. Forecasting prospective changes in land cover/use generally require the application of spatio-temporal land-use models. Such models engage time-series historical land-use trends, in combination with the concerned biophysical and socio-economic factors provoking the changes, to establish close-to-optimal realistic future scenarios (Verburg *et al*., 2002; Githui *et al*., 2009). More recently, research efforts have been made to integrate land-use, hydrologic and atmospheric models to enable compact analyses of the effects of environmental change and variability to facilitate adaptation and mitigation (Solecki *et al*., 2004; McColl and Aggett, 2007). In developed countries especially, such conventional modelling tools have been widely used to support policy options for environmental monitoring and management. However, their application in developing countries is still hampered by poor data infrastructure and limited technical capacities. In the NRB for instance, the most reliable population data required for assessing the demographic change trends was collated more than two decades ago. Furthermore, the sub-catchments in the basin do not have dependable time-series land-use and streamflow data for a comprehensive distributed and calibrated hydrological modelling approach (Refsgaard and Henriksen, 2004; Olang and Fürst, 2011). In such areas therefore, it is imperative that reasonable modelling procedures are formulated and tested to provide baseline information required for enhanced land and water management. Such an endeavour is a significant step towards providing straightforward solutions, especially with the present requirement for an integrated approach towards environmental management.

Considering the increasing availability of global spatial datasets consequent of advances in remote sensing techniques, a feasible modelling option in areas with data scarcity is the application of physically based hydrologic models. Such models describe the interactions of different hydrologic variables by using empirical equations that relate to physically observable land surface characteristics. Consequently, these models have been extensively employed in estimating the effects of landscape variability within the tropical catchments with data constraints (Gathenya *et al*., 2011; Opere and Okello, 2011; Mati *et al*., 2008; Kundu *et al*., 2008; Legesse *et al*., 2003). Today, such physically based model parameters can be consistently derived from the available spatial datasets with the help of a geographical information system (GIS) (Carpenter *et al*., 1999; Callow *et al*., 2006). In this contribution therefore, the specific objectives of study were as follows: (i) to assess the hydrologic vulnerability of Nyando basin in terms of flood runoff volumes consequent of conceptual land cover scenarios by using empirical hydrologic models the parameters of which could be physically derived from global datasets; this included evaluating the possible runoff bandwidth consequent of the scenarios in order to assess the scenario that could be used to minimize flood runoffs for purposes of catchment management; (ii) to assess the overall response of the entire Nyando basin if the most appropriate scenario was to be assumed for purposes of runoff management in the respective 14 sub-catchments of the basin.

THE STUDY AREA

The NRB is located in western Kenya and covers an area of about 3550 km^2. The basin spans the Equator between 0°25′ S–0°10′N and 34°50′E–35°50′E. It has its upland foot slopes along the Nandi Hills and Mau Escarpments, located at altitudes of about 2300 m on the northern side and 2800 m on the eastern side, respectively. The basin is drained by River Nyando, with a total length of about 170 km, draining into Lake Victoria at an altitude of about 1100 m above mean sea-level. The basin exhibits diverse land use/land cover patterns, influenced a lot by rainfall seasonality and socio-cultural practices. The major land cover types vary largely from forests in the headwater catchments to medium-scale and small-scale subsistent agriculture in the central and lower parts of the basin, respectively. A typical characteristic in the floodplains of the Nyando basin are the occurrence of floods, which are augmented largely by uncontrolled anthropogenic activities consequent upon the rising human population (Olang and Fürst, 2011). The rainfall seasons of the basin can be classified as bimodal, with the LRS experienced from March to May (MAM) and the short rainy season (SRS) between September and December (SOND).

Normally, the diurnal and seasonal rainfall patterns of the region are influenced by the movement of the Inter-tropical Convergence Zone modified by local orographic effects. However, inter-annual variabilities due to El Niño/Southern Oscillation are occasionally witnessed (Anyah and Semazzi, 2004; Anyah and Semazzi, 2007). Mean annual rainfall amounts of about 1600 mm are prevalent within the uplands of the basin, with a majority of the storm events having average daily depths of about 80 mm. The storms here are less intense and with relatively longer durations, sometimes of up to 10 h during the LRS. In the dry lowlands, however, mean annual rainfall amounts of about 800 mm are prevalent, with a majority of the events exhibiting depths of about 40 mm. The storms are generally highly intense but of shorter duration in the range of 1–5 h. Considering these

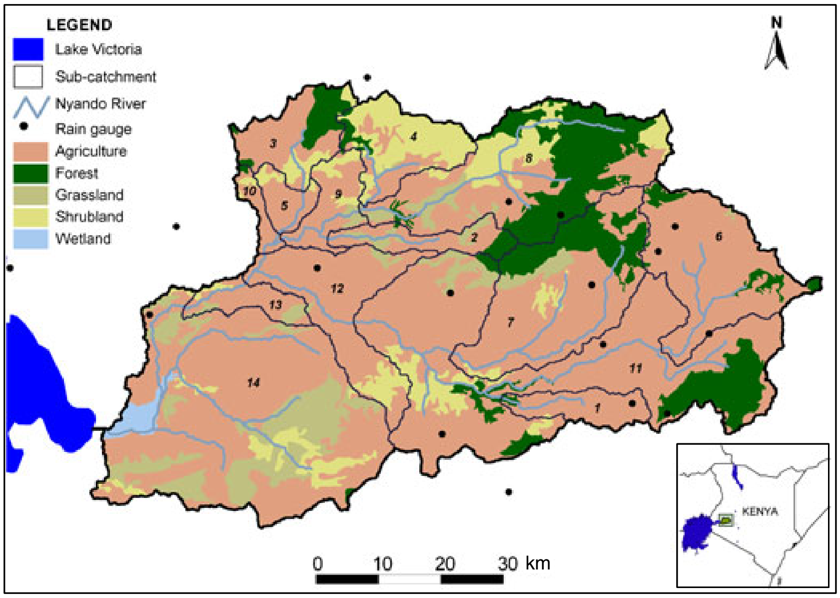

Figure 1. Land cover (in 2000) and the sub-catchments of the Nyando River basin. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

spatial and temporal rainfall patterns therefore, hourly synthetic storm events of depths 40, 60 and 80 mm were formulated for study and applied uniformly across the sub-catchments of the basin. The events were also assumed to exhibit the same durations corresponding approximately to the average times of concentration of runoffs in the respective sub-catchments (ASCE, 1993; Olang, 2009). The sub-catchments delineated for the study and the land cover state of the basin in the year 2000 are illustrated in Figure 1.

TOOLS AND METHODS

The Hydrological Models

Runoff generation and transformation

The United States Natural Resource Conservation Service–Curve Number[4] (US-NRCS-CN) model was used to generate runoff volumes [United States Association for Civil Engineers (USACE), 1994]. The potential of the model to represent land surface conditions by using the dimensionless curve number (CN) parameter, which can be physically approximated from spatial datasets makes the model readily applicable in data-constrained regions such as Kenya (Olang *et al*., 2011; Githui *et al*., 2009). The underlying assumption of the model is that effective rainfall is the portion of the total rainfall less the initial abstractions. The other assumption is that the arising infiltration is less than or equal to the potential maximum retention. Under these conditions therefore, the volume of runoff is generated on the basis of the following ratios:

$$\frac{F}{S} = \frac{Q}{R_e} \tag{1}$$

Where: F is the infiltration, S is the maximum potential retention, Q is the actual runoff and R_e is the effective rainfall potentially causing the runoff. The runoff depth can then be estimated from the relationship:

$$Q = \left(\frac{(R_T - I_a)^2}{R_T - I_a + S}\right) = \frac{R_e^2}{R_e + S} \tag{2}$$

Where: R_T is the total precipitation, which is the sum of losses due to the initial abstraction (I_a), actual runoff (Q) and infiltration (F). Normally, the above model parameters are consistently expressed in units of either length (mm) or volume (m^3).

Studies by the US-NRCS (Mutua and Klik, 2007; USACE, 1994) have shown that the initial abstraction can be assumed to account for 20 per cent of the maximum potential retention (S), which can be further related to the dimensionless CN parameter as follows:

$$S = \frac{25\ 400}{CN_m} - 254 \tag{3}$$

Where: CN_m is the composite CN parameter, normally ranging between 0 and 100 per cent. Generally, higher values of the CN parameter indicate small rainfall losses leading to high runoff volumes during storm events. In this study, the corresponding composite CNs for the sub-catchments of the region were obtained from the land use and soil datasets

[4]Formerly known as United States–Soil Conservation Service–Curve Number.

through a zonal summary achieved in a GIS. The derived composite CN represented average values of the parameter under normal antecedent soil moisture conditions. However, during storm events of the Nyando basin, it is often the case that the catchments are under wet moisture condition because of prolonged periods of seasonal rainfall. Consequently, additional empirical procedures that relate the normal (AMC II) to the wet moisture conditions (AMC III) were used to obtain the actual CNs for the sub-catchments during the storm conditions (Onyando, 2000; Ponce and Hawkins, 1996).

The Clark's unit hydrograph (UH) model was used to transform the generated runoff volumes into corresponding hydrograph within the sub-catchments (USACE, 1994; Kull and Feldman, 1998; Olang, 2009). Unlike other conceptual unit hydrograph concepts, the model allows for the estimation of its parameters from physically based catchment characteristics. The model translates an instantaneous rainfall excess on the basis of its travel times while accounting for its transitory storage to the outlet of the sub-catchment. The translation hydrograph is routed through a single linear reservoir to generate an instantaneous UH, representing an outflow assumed to fill instantaneously with a unit volume of precipitation excess. In this study, the translation hydrograph was estimated from the dimensionless time–area relationship expressed as

$$\frac{A(t)}{A_{\mathrm{T}}} = \begin{cases} 1.414\left(\frac{t}{t_c}\right)^{1.5} & \text{for } t \le \frac{t_c}{2} \\ 1-1.414\left(1-\frac{t}{t_c}\right)^{1.5} & \text{for } t > \frac{t_c}{2} \end{cases} \tag{4}$$

Where: $A(t)$ is the area of the sub-catchments (km^2) contributing the runoff at time (t), whereas t_c represents the time of concentration of the runoffs in hours (h). Generally, the time of concentration was assumed to be approximately 1·67 times the lag time (Soil Conservation Service, 1986; Straub *et al*., 2000). The other parameter also required by the Clark's UH model is the transitory storage coefficient of the basin. This was achieved on the basis of the following relationship (Sabol, 1988; USACE, 1994; Olang, 2009):

$$\frac{t_c}{R} = 1.46 - 0.0867\frac{{L_h}^2}{A} \tag{5}$$

Where: R is the storage coefficient, t_c is the time of concentration in hours (h), L_h is the hydraulic length of the catchment in metres (m) and A is the area of the sub-catchment in km^2. Generally, as changes in land cover conditions can modify the runoff flow paths, an empirical procedure that relates the flow travel times and composite CN parameters were adopted in this study. The relevant geophysical properties of the area, including the hydraulic length, the average slopes of the stream channels and sub-catchments required for the estimation of the translation hydrograph were derived from a digital elevation model (DEM) of the area.

Baseflow and streamflow routing

The baseflow decay during the storm events was generally modelled using the exponential recession model according to the relationship (Pilgrim and Cordery, 1992):

$$Q_t = Q_0 k^t \tag{6}$$

Where: Q_t is the baseflow at time (t); Q_0 the initial baseflow discharge in m^3 s^{-1} and k is an exponential decay constant. The initial baseflow within the sub-catchments during the rainy season were assumed to be bank full and estimated through physical measurement. The physically based Muskinghum–Cunge hydrologic model was used to route the arising flows from the sub-catchments (Ponce, 1989; Olang and Fürst, 2011). Physically based parameters of the model were established through measurements of the stream channels characteristics, coupled with GIS derivations from spatial datasets, at selected river reaches within the sub-catchments. Empirically, the model routes flow based on the principle of mass conservation expressed as follows:

$$\frac{I_1 + I_2}{2}\Delta t - \frac{O_1 + O_2}{2}\Delta t = S_1 - S_2 \tag{7}$$

Where: I_1, I_2 and O_1, O_2 are the respective inflow and outflow discharges in m^3 s^{-1} at times (1) and (2), respectively, Δt represents the time difference between the flows in seconds (s), S_1 and S_2 are the volumetric storage values in m^3 at the times. The relationship between storage, inflow and outflow parameters at the river reach under consideration can be generally represented empirically in the following:

$$S = K\{XI + (1 - X)O\} \tag{8}$$

Where: S is the storage in m^3, K is the travel time of the flood wave through routing reach in seconds (s), X is a dimensionless weighing factor, and I and O are the inflow and outflow discharges. The dimensionless weighing factor accounts for the relative effects of inflow and outflow on storage, normally ranges between 0 and 5 depending on the channel slope characteristics. For the study, the parameter was estimated on the basis of the following equation:

$$X = \frac{1}{2}\left(1 - \frac{Q_0}{BS_0 c\Delta x}\right) \tag{9}$$

Where: Q_0 is the reference inflow in m^3 s^{-1}; B is the top width of the flow in metres (m); S_0 is the river bed slope in m m^{-1}; c is the flood wave velocity in m s^{-1}; and Δx is the length of the routing reach in metres (m). The flood wave velocity was estimated from the mean flow velocity derived using Manning's relationship (Viessman *et al*., 1989; Olang, 2009). Generally, the Muskinghum–Cunge hydrologic model parameters, including the river channel length and slopes of the selected river reaches, were from spatial datasets. Additional data for the model were also obtained from

Lake Victoria Environmental Program in Kenya. Detailed empirical relationships of the Muskinghum–Cunge model and the hydraulic catchment-based properties can be obtained from hydrological literature (e.g. Chow *et al.*, 1988; Ponce, 1989) among others.

Spatial Datasets and Catchment Parameters

The physically based properties of the basin were derived from a hydrologically corrected DEM. The 90 m × 90 m dataset, produced through the global Shuttle Radar Topographic Mission, was acquired and processed to derive the sub-catchments and their morphometric characteristics based on standard GIS procedures that simulate flow directions and accumulation (Callow *et al.*, 2006; Reuter *et al.*, 2007). The derived stream networks were later realigned to their actual spatial locations with the help of a geo-referenced Landsat satellite image of the area for the year 2000. Data for outlining the state of land cover in the year 2000 were obtained from the FAO-Africover land cover website. The multipurpose land cover dataset at a scale of 1:100 000 was acquired as vector coverage, processed and reclassified into the required land cover classes with the help of the FAO-UNESCO land cover classification manual (FAO-UNESCO, 1988, FAO, 1997). A digital soils data for Kenya at a scale of 1:1 million was also obtained from the Global Environment Facility–Soil Organic Carbon database (Batjes and Gicheru, 2004), processed and used to derive the major hydrological soil groups (HSG) according to their drainage characteristics (Figure 2). Normally, soils in hydrological soil group (A) are deep, well drained and with high rates of infiltration when thoroughly wet. Conversely, soils in hydrological soil group (D) are poorly drained, have very slow water transmission rates and hence high runoff potential under wet conditions. The derived HSGs, together with the land cover data for the formulated scenarios, were subsequently used to estimate the composite CN parameter of the sub-catchments under normal moisture conditions (AMC II). Look-up tables for retrieving the initial CN parameter values were developed from standard tables provided in hydrological literature (e.g. Chow *et al.*, 1988; Maidment, 1993).

Formulation of the Land Cover Scenarios

The land cover scenarios were formulated considering the historical trends of previously detected land cover changes witnessed between 1973 and 2000 (Olang *et al.*, 2011). In this work, the authors revealed varying proportions of the land cover changes in time and space. A critical assessment of the land cover conversion matrices across the sub-catchments disclosed significant deforestation in the headwaters, with the highest change in forests, agriculture and shrublands, during the period of study, being 37, 24 and 8 per cent, respectively. In the downstream sub-catchments, however, subtle changes that varied between agriculture and grasslands on seasonal basis were predominantly noted. The highest change in the forest, agriculture and shrublands in this region principally stood at about 12, 27 and 15 per cent, respectively. In view of these spatio-temporal change patterns, this study presumed that changes in the land cover patterns for each sub-catchment could generally fluctuate between full deforestation and reforestation depending on the management conditions. The conceptual scenarios of study were thus selected within this bandwidth to enable an evaluation of the scenario to be targeted for reduced flood runoff volumes within the sub-catchments.

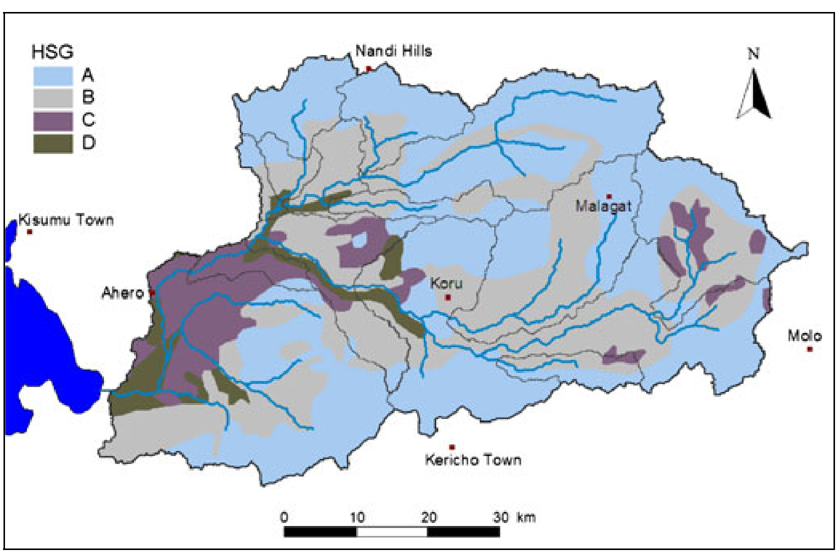

Figure 2. Hydrological soil groups (HSG) of the Nyando River Basin. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

Three general conceptual spatial scenarios that attempted to compromise the diverse spatio-temporal land cover changes were consequently formulated and assumed to apply equally to the sub-catchments. The first scenario (scenario 1) largely constituted 5 per cent of forest, 86 per cent of agriculture and 5 per cent of grassland by proportions. The agricultural scenario generally typifies a situation where a majority of the land is under cultivation, subject to increasing socio-economic human activities. The second scenario (scenario 2) exemplifies an agricultural-forested situation where about 40 and 51 per cent are reserved for forests and agriculture, respectively. The third scenario (scenario 3) illustrates a more forested land cover state constituting about 78 and 10 per cent of forests and agriculture, respectively, as the major classes. The forested scenario, therefore, presumes a reforestation management programme with equivalent proportions of the land cover classes. The overall proportions of land cover classes for the scenarios, in comparison with the actual land cover state of basin in the year 2000, is illustrated Figure 3.

RESULTS AND DISCUSSION

Estimated Geophysical Parameters of the Sub-catchments

The major catchment parameters derived from the global spatial datasets are provided in Table I. Estimates obtained from the actual land cover state in 2000 are also provided in the table. Moreover, the parameters have been sorted out according to the sub-catchment identities in Figure 1.

From Table I, an agricultural land cover scenario (Sc. 1) exhibited the highest composite CN parameter values for the sub-catchments as compared with the other two scenarios (i.e. Sc. 2 and Sc. 3). From the general US-NRCS model assumption that higher values of CN parameter translates to higher runoff potential, the sub-catchments of the basin thus can be construed to be more vulnerable to higher runoff volumes under scenario 1. In terms of the hydraulic properties, sub-catchment no. 14 (Lower-SB) provided the largest relative storage coefficient parameter for the scenarios. This parameter is an indication of the transient storage capability of a region, especially during storm events. In a majority of cases, larger catchments tend to exhibit higher value of this parameter due their larger geometric advantages (Olang and Fürst, 2011). However, this was not strictly the case with our findings in this study. The derived value of the parameter for sub-catchment no. 5 (Kapchure 2) with a smaller catchment area, for instance, provided the second largest storage coefficient parameter. This variation could perhaps be attributed to the varied topography and soil characteristics of the region. Normally, as changes in the state of land cover can, sometimes, lead to modification of flow paths and hence the runoff times of concentration, the derived storage capacities of the sub-catchments were noted to fluctuate considerably across the scenarios. Compared with the actual land cover state in the year 2 000, the derived CNs, times of concentration and storage coefficients revealed significant variations across the sub-catchments according to the spatial land cover patterns and geophysical characteristics.

It is worth noting that the derived composite CN parameters in Table I were lumped at the sub-catchments scales through a zonal summary achieved in a GIS. In reality, however, this parameter has been noted to be highly random in space and time because of non-linearity of the moisture conditions important for its derivation (Chow *et al*., 1988). Its accurate determination in areas with limited data provisions, therefore, is still a major challenge to many hydrological studies in data-constrained areas. Besides this parameter, other studies have also demonstrated that the times of concentration, and hence the storage coefficients, estimated using the US-NRCS method sometimes tend to exhibit variations dependent on the input parameters (ASCE, 2007;

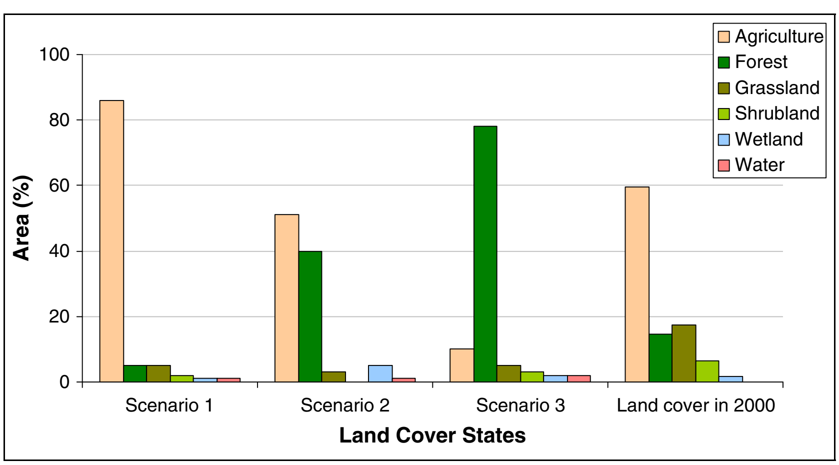

Figure 3. Proportion of the land cover types of study. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

Table I. Derived geophysical parameters for the sub-catchments

ID	Name of sub-catchment	Area (km^2)	Average slope (%)	Hydraulic length (km)	Composite curve numbers (%)				Storage coefficient (*h*)			
					Sc. 1	Sc. 2	Sc. 3	LC-2000	Sc. 1	Sc. 2	Sc. 3	LC-2000
1	Tugunon	73·7	15·0	8·0	80·6	66·6	62·1	75·8	1·2	1·7	1·9	1·5
2	Mbogo	77·2	18·7	8·9	81·2	70·6	63·4	74·3	2·1	2·9	3·5	1·6
3	Kapchure1	130·7	13·2	6·9	77·6	70·3	64·5	72·1	3·0	3·7	4·3	1·6
4	Ainapsiwa	147·7	16·6	6·7	78·0	70·6	64·5	74·3	2·1	2·6	3·1	1·3
5	Kapchure2	45·3	12·0	4·0	80·5	71·5	65·2	78·9	3·3	4·3	5·1	0·9
6	Masaita	285·6	8·0	10·4	78·3	68·7	61·9	71·9	0·9	1·2	1·4	2·8
7	Namuting	365·3	17·2	14·7	79·4	70·0	63·7	71·2	1·3	1·6	1·9	2·6
8	Ainamotua2	446·4	18·4	17·7	72·5	65·5	61·9	64·0	1·7	2·0	2·2	3·6
9	Ainamotua3	83·4	12·7	6·3	84·6	75·5	68·8	82·5	2·8	3·8	4·6	1·1
10	Ainamotua1	28·4	13·7	4·6	81·7	74·3	65·7	78·9	1·0	1·3	1·6	0·9
11	Nyando3	747·6	13·5	23·9	78·2	71·6	64·6	72·9	1·4	1·7	2·0	4·2
12	Nyando2	220·6	6·2	11·5	83·4	74·5	68·8	82·5	2·0	2·7	3·1	2·6
13	Nyando1	61·2	2·2	7·4	83·3	73·3	63·6	87·3	0·8	1·1	1·4	2·6
14	Lower-SB	830·5	6·5	18·5	80·7	72·4	66·4	80·1	3·8	4·9	5·7	3·9

Sc. 1, agricultural scenario; Sc. 2, agricultural-forested scenario; Sc. 3, forested scenario; LC-2000, land cover state in 2000.

Olang, 2009). Bearing in mind these sources of modelling uncertainties, including the spatial scale adopted and the incapacity to calibrate the model results against observed data, it was important for us to understand the reliability of the estimates in Table I for subsequent use in reliably replicating the runoff response of the basin. Expert judgment and plausibility checks was hence performed to compare the results against recent studies in the basin that have applied a similar approach (e.g. Olang *et al.*, 2011; Opere and Okello, 2011; Olang and Fürst, 2011). The result obtained indicated the derived parameters, and results, generally proved consistent enough to provide robust simulation estimates. Furthermore, as the study also focussed on relative land cover change effects, it was also possible that propagation of the structural model errors was minimized in the percentage relative increases or decreases obtained for the basin.

Simulated Runoff Volumes in the Sub-catchments

The estimated flood runoff volumes for the 14 sub-catchments obtained using the three synthetic storm events are illustrated in Table II. For comparison purposes, especially for runoff management purposes, the simulated estimates were evaluated relative to the actual land cover state in 2000.

From Table II, simulated estimates from the land cover state in 2000 (LC-2000) indicated that sub-catchment no. 2 (Mbogo) experienced runoff volumes of about $8 \times 10^6\,m^3$ from the 60 mm storm event. The sub-catchment is located in the middle uplands of the basin, an area that has witnessed one of the highest conversion of forested lands into commercial and subsistence agriculture over the years. An increased agricultural area in the region (scenario 1), therefore, would lead to increased flood volumes to about $11 \times 10^6\,m^3$. In the same area, scenarios 2 and 3 would reduce runoff volumes to about $9 \times 10^6\,m^3$ and $8 \times 10^6\,m^3$, respectively. In terms of runoff management, both scenarios 2 and 3 can be considered appropriate, with the former being more quickly feasible considering the existing socio-economic activities. In sub-catchment no. 3 (Kapchure 1) located on the northern upstream part of the basin, about $2 \times 10^6\,m^3$, $1{\cdot}6 \times 10^6\,m^3$ and $1{\cdot}3 \times 10^6\,m^3$ volumes of runoff were produced for scenarios 1 (Sc. 1), 2 (Sc. 2) and 3(Sc. 3), respectively, from the 40 mm storm event. In terms of the flood runoff bandwidth, this signifies a disparity of up to $7 \times 10^5\,m^3$ between the land cover alternatives represented by scenarios 1 and 2. Compared with LC-2000, however, the estimates represent an increase by about 6 per cent for Sc. 1 and decreases of about 18 and 30 per cent for Sc. 2 and Sc. 3, respectively. In this particular sub-catchment, flood runoffs would be significantly reduce under an agricultural-forested scenario and a forested scenario. Generally, among the spatial alternatives of study, the highest increase in runoff volumes for an agricultural scenario was noted in sub-catchment no. 9 (Ainamotua3). From the 60 mm storm event for instance, an increase of about 28 per cent from the scenario and consequent decreases of about 3 and 19 per cent for Sc. 2 and Sc. 3 were observed relative to the LC-2000. Thus, in the area, runoff reduction was more likely under Sc. 2 and Sc. 3.

On the contrary, sub-catchment no. 14 (Lower-SB) located in the lowlands generally indicated the lowest decrease in the runoff volumes for a forested land cover scenario. Here, an increase of about 2 per cent for Sc. 1 and decreases of about 21 and 34 per cent for Sc. 2 and Sc. 3, respectively, were noted from the 80 mm storm event. In reality, this sub-catchment exhibits a region with limited forests due to intense cultivation arising from the encroaching population from the vicinity of Kisumu Town located on its west. Considering the land-use dynamics associated with

Table II. Simulated runoff volumes ($\times 10^6$ m^3) for the sub-catchments

	40 mm synthetic storm				60 mm synthetic storm				80 mm synthetic storm			
ID	Sc. 1	Sc. 2	Sc. 3	LC-2000	Sc. 1	Sc. 2	Sc. 3	LC-2000	Sc. 1	Sc. 2	Sc. 3	LC-2000
1	1·00	0·88	0·79	0·96	1·40	1·22	1·06	1·34	1·49	1·30	1·12	1·43
2	5·55	4·43	3·96	4·22	10·62	8·66	7·80	8·28	11·75	9·62	8·68	9·21
3	2·00	1·55	1·32	1·88	3·26	2·56	2·16	3·08	3·53	2·79	2·35	3·34
4	2·29	1·80	1·50	2·03	4·23	3·40	2·86	3·79	4·65	3·76	3·17	4·18
5	1·97	1·55	1·28	1·65	3·67	2·95	2·48	3·12	4·04	3·27	2·76	3·44
6	0·83	0·63	0·52	0·80	1·47	1·13	0·94	1·40	1·60	1·24	1·04	1·54
7	4·40	3·20	2·60	3·54	8·16	6·14	5·05	6·73	8·98	6·80	5·61	7·45
8	1·36	0·96	0·78	1·09	2·46	1·80	1·47	2·01	2·70	1·99	1·63	2·21
9	5·88	4·30	3·54	4·46	10·82	8·18	6·82	8·45	11·90	9·05	7·57	9·35
10	2·18	1·84	1·63	2·37	3·09	2·55	2·18	3·37	3·29	2·71	2·31	3·58
11	5·06	3·95	3·45	4·92	8·36	6·60	5·73	8·15	9·07	7·18	6·25	8·84
12	11·51	9·22	7·41	9·54	21·31	17·50	14·29	18·02	23·46	19·35	15·85	19·96
13	1·31	0·85	0·76	1·12	2·34	1·58	1·40	2·04	2·57	1·75	1·55	2·24
14	14·79	11·15	9·19	14·48	26·38	20·36	16·88	25·89	28·92	22·50	18·73	28·40

the up-surging human population, it is less likely that runoff management under scenario 3 is achievable. Scenarios 2 can thus be assumed as more likely for this area. From the results obtained in general, the sub-catchments of the Nyando basin were noted to respond diversely to the effects of the land cover scenarios. A majority of the sub-catchments consequently indicated probable reduced flood runoff volumes under more than one scenario. It was hence imperative to identify a general criterion that could be used to select the appropriate scenario for the runoff management. Consequently, the scenario that provided a reduction (decrease) of not less than 10 per cent was thus arbitrarily assumed. With this criterion, runoff reductions in a majority of the regions were noted to be more feasible under scenario 2. Alternatively, scenario 3 was equally noted as appropriate for sub-catchments nos. 1 (Tugunon), 5 (Kapchure2), 7 (Namuting), 9 (Ainamotua3) and 12 (Nyando2). However, the relative decrease in the runoff volumes was noted to be less than the defined criteria in sub-catchment no. 2 (Mbogo). As such, the alternative closest to the defined criterion was selected as the best option. Figure 4 illustrates how the spatial proportions of scenario 2 considered as the most appropriate for reduced flood runoffs in sub-catchment no. 6 (Masaita) compared with the actual states of the land covers in the year 2000.

Sub-catchment no. 6 (Masaita) located in the headwaters of the Nyando basin forms part of the MFC highly affected by deforestation due to anthropogenic activities. More recently, efforts have being made by the government to restore the MFC region as it forms a major catchment area for a majority of rivers in the country (Olang and Kundu, 2011). From the results of our study, an afforestation programme in Masaita region that would increase the forest covers by about 26 per cent, while decreasing agriculture by 31 per cent as is assumed under scenario 2, is capable of minimizing flood runoffs in the sub-catchment by about 21 per cent. However, if the area of forests is increased by 64 per cent and agriculture reduced by 72 per cent, as is the

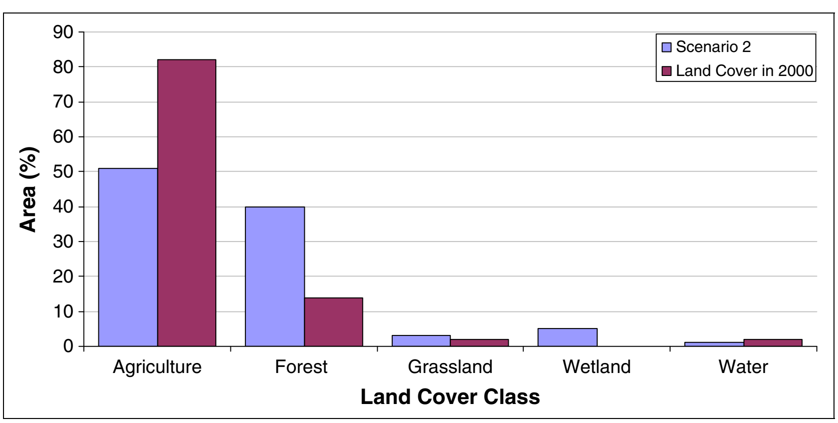

Figure 4. Distribution of land cover states in scenario 2 selected for runoff management and in the year 2000 for sub-catchment no. 6 (Masaita). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

Table III. Simulated runoff volumes within the entire Nyando River basin

Rainfall depth (mm)	Simulated flood runoff volumes ($\times 10^6$ m^3)					Changes relative to LC-2000 (%)			
	Sc. 1	Sc. 2	Sc. 3	RM-Sc.	LC-2000	Sc. 1	Sc. 2	Sc. 3	RM-Sc.
40	58·85	45·41	37·81	43·46	51·75	−13·7	12·3	26·9	16·0
60	105·22	82·76	69·30	79·37	93·45	−12·6	11·4	25·8	15·1
80	115·30	91·09	76·79	87·78	102·86	−12·1	11·4	25·3	14·7

case with scenario 3, then the consequent runoff volumes can be reduced by 35 per cent. However, considering the existing socio-cultural activities of the area, this is a very optimistic scenario that would require ancillary reorganization of the resettlement patterns.

Effects of the Land Cover Changes in the Entire Basin

To evaluate the resulting effects of the land cover changes within the entire NRB, we accrued and routed the runoff volumes from the sub-catchments to the final outlet of the basin. The relative results obtained are illustrated in Table III. Also provided in the table is the response of the basin if the most appropriate scenario for the respective sub-catchments was assumed for purposes of catchment management. The scenario is herein identified as the runoff management scenario (RM-Sc.).

From the results, an agricultural land cover scenario would increase runoff volumes by approximately 14, 13 and 12 per cent from the 40, 60 and 80 mm synthetic storms, respectively. In volumetric terms, these values represents increases by about $7{\cdot}1 \times 10^6$ m^3, $11{\cdot}8 \times 10^6$ m^3 and $12{\cdot}4 \times 10^6$ m^3 relative to LC-2000. From the same order of storm events, an agricultural-forested land cover scenario would produce runoff volumes of about $45{\cdot}4 \times 10^6$ m^3, $82{\cdot}8 \times 10^6$ m^3 and $91{\cdot}1 \times 10^6$ m^3, representing volumetric decreases by about $6{\cdot}3 \times 10^6$ m^3, $11{\cdot}7 \times 10^6$ m^3 and $11{\cdot}8 \times 10^6$ m^3, or variations by about 12, 11 and 11 per cent, respectively. According to the model estimates, a forested land cover scenario was also noted to result into significant reduced runoff volumes in the basin. From simulated values, decreases of about 27, 26 and 25 per cent were probable from the three storms. Using the assumed scenarios for the respective sub-catchments, runoff volumes were likely to reduce by about 16, 15 and 15 per cent from the respective synthetic storms. Also apparent from the results was a decreasing trend in the relative percentage variations with increasing depths of the rainfalls. The 40 mm storm event for instance generally produced higher percentage variations than the 80 mm storm event, indicating the possibility that the land cover changes could have limited effects during very large storm events.

Apart from flood runoff volumes emphasized more in this study for purposes of catchment management, other runoff hydrographic characteristics also of generally concern for water resources management include the peak discharges and duration to peak. Figure 5 illustrates the simulated flood runoff hydrographs for the Nyando basin obtained from the 80 mm synthetic storm events. From the figure, scenario 1 generally produced larger flood peak discharges (about 4500 m^3 s^{-1}) within shorter durations of times compared with the others. Although peak discharges for scenario 2 and LC-2000 tended to be closer to each other from the hydrographs, the former was noted to reach its times to peak 1 h earlier than the latter. However, almost similar to scenario 2 in terms of the times to peak, but with a lower peak discharge value, was the results provided by RM-Scenario. Compared with scenario 2 and LC-2000, therefore, this scenario can be a considered an initial target for reducing consequent flood peak discharges, times to peak and runoff volumes within the sub-catchments and in the entire basin.

CONCLUSION

With the use of a hydrological modelling approach applicable within the largely ungauged NRB, this study tested the effect of conceptual land cover change scenarios on the generation of storm runoffs for purposes of catchment planning and management. Considering the prevalent data uncertainty in the basin, the study relied on plausibility checks and hydrological experience to understand the reliability of the simulated runoff volumes in comparison with other studies in such area. The study, therefore, highlights the potential hydrological vulnerability of the area by providing catchment-specific statistics of how enlarged deforestation and afforestration would affect runoff volumes. Furthermore, it exemplifies how storm runoff volumes can be significantly reduced if the most appropriate option of the formulated scenarios was to be assumed within the respective sub-catchments of the basin. In comparison with previous simulation studies based on a similar approach in the NRB of Kenya, the results obtained compares very well and can hence be used to support decision making aimed at improving land and water management. However, as the conceptual land cover scenarios were formulated without taking into account the demographic and other socio-economic factors influencing the eminent land-use dynamics, it is important for future studies to consider this in defining more realistic

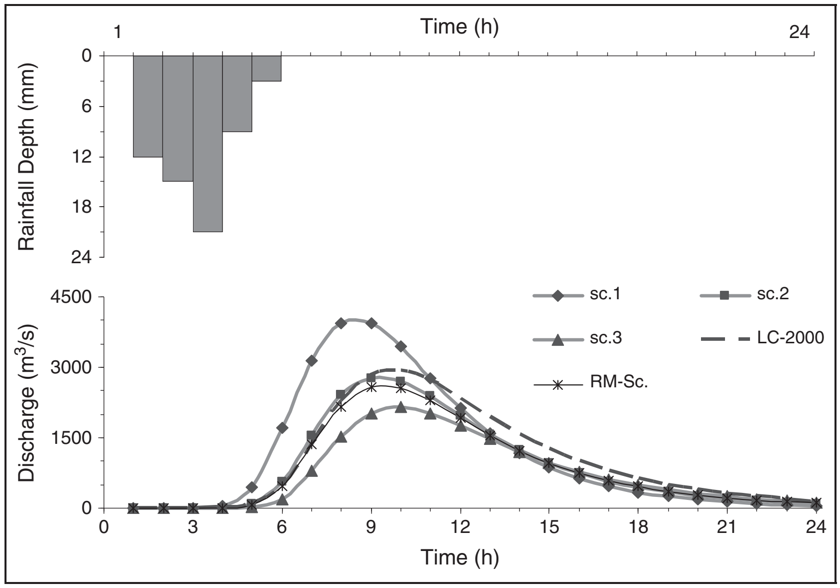

Figure 5. Simulated flood runoff hydrographs for the Nyando basin obtained from the 80 mm synthetic storm event.

land cover scenarios. This may require involving fully distributed land-use modelling approaches capable of characterizing the spatial and temporal distribution of prospective land use changes. In terms of the hydrological modelling approach adopted, spatial scaling was achieved at sub-catchment levels as the flow routing parameters could only be estimated at this locations. It is hence possible that this lumping procedure could have led to uncertainty related to loss of spatial information. It is thus vital that a more distributed hydrological modelling approach that can capture the random and non-random patterns of the hydrological processes be considered in future. Also important will be the need to couple the appropriate land use, hydrologic and atmospheric models to enable compact analyses of the effects of concerned environmental changes and variability.

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