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Modeling the impact of land use changes on river flows in Arror watershed, Elgeyo Marakwet County, Kenya

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Abstract

Water scarcity has become a serious global problem. Therefore, there is an urgent need to understand land use changes in watershed areas and their impact on river flows. This study models the impact of land use changes on river flows in the Arror watershed in Elgeyo Marakwet County, Kenya. The primary study sources included remotely sensed and socio-economic data. Landsat 5 thematic mappers for 1986, 2000 and 2012 (resolution 30 m) were used. A 90 m Digital Elevation Model resolution was used to delineate the Arror watershed. Secondary data included climate, river discharge and soil data. Field surveys and questionnaires were used to collect socio-economic data. GIS was integrated with a Soil and Water Assessment Tool model to determine the impact of land use changes on water quantity. The calibration goodness of fit results for the model were 0.9 and 0.8, for EF (Nash-Sutcliffe Efficiency) and R-squared, respectively. The results show a reduction of 3.5% of deciduous forest and 11.8% of grassland, while agricultural land increased by 14.3% from 1986 to 2012. The 1986, 2000 and 2012 land uses yielded an annual average flow of 2.0, 2.5 and 1.9 m^3/s respectively. Flow variation was attributed mainly to land use changes. Agroforestry and afforestation are recommended for sustainable watershed management.

Key words: Arror, catchment, GIS, streamflow, SWAT

INTRODUCTION

Water is a major natural resource, and is crucial for life and for sustainable development. The fact that the earth's water is constantly in motion, changing states and location, makes rational planning and management complex and difficult (Turner *et al.* 2004). Moreover, the availability and use of water is mainly constrained by its spatial quantity and quality distribution.

Water resource volumetric degradation is a serious national and international problem, affecting economic productivity and the environment in many ways. Water shortages cause widespread health problems, limiting economic and agricultural development, and harming a wide range of ecosystems. According to Mwiturubani & Wyk (2010), reports from the United Nations Environment Programme confirm that in 2010 severe water shortage was affecting 400 million people worldwide and was projected to affect four billion people by 2050. Water resources touch every sector of the economy, so it is important to improve their management, to reduce degradation, and enhance equitable access and utilization, thus reducing sources of conflict (Mwiturubani & Wyk 2010).

In Kenya, water resources underpin the country's main economic sectors: agriculture, livestock, tourism, manufacturing and energy. The social, economic and environmental aspects of water signify its importance in the country's sustainable development, attainment of Vision 2030 targets and

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realization of human rights, as stipulated in the Constitution of Kenya 2010. Kenya's renewable freshwater resources are estimated at 20.2 km^3/a, which corresponds to 647 m^3 per capita, one of the lowest in Africa. The situation is expected to worsen due to population growth and climate change (Republic of Kenya [ROK] 2002). Roughly a third of Kenya's population has no access to safe water supplies and nearly 50% live below the absolute poverty line, while the national economy and environment are struggling with the negative effects of deforestation, poor land management and water shortages (Muchemi *et al.* 2002).

The Arror River watershed, in the Kerio River Basin, represents typical semi-arid and dry, sub-humid, rain-fed, agrarian conditions. The watershed manifests strong signs of human-induced land degradation due to high pressure on soil and water resources, where land use changes upstream are affecting river hydrology downstream. Increased pressure on the finite arable land due to increasing human population is also causing unprecedented land degradation as communities seek agricultural land on steep slopes and in wetlands, and use poor farming methods (Muchemi *et al.* 2002).

A pressing need exists, therefore, to develop environmentally sustainable and socially equitable approaches to water development and management, to balance the needs of the environment with economic growth, while addressing widespread poverty and lack of water, and eliminating water-related disasters. This is in line with goal 15 of the UN's Sustainable Development Goals, which emphasize conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains and dry lands, in accordance with obligations under international agreements (Sachs 2012). Against this background an effort was made to model the impacts of land use changes on water quantity in the Arror River watershed. This was done by simulating and describing the impacts of land use on watershed response using the Soil and Water Assessment Tool (SWAT) model.

MATERIALS AND METHODS

Study area

The study area comprises the regions draining water into the Arror River, a tributary of the Kerio River. The area is in Elgeyo Marakwet County, Kenya. The river rises in the eastern part of Cherangani Hills, the bulk of the catchment being in the Embobut and Kipkunur forests, at altitudes between 3,200 and 2,300 m above sea level (Kerio Valley Development Agency [KVDA] 1989). The river flows through three administrative divisions of Marakwet East and West, the sub-counties of Kapyeko, Kapsowar and Tunyo, and extends from latitude 0° 51′ to 1° 19′ North, and longitude 35°15′ to 35° 45′ East. The watershed covers approximately 285 km^2 and is the largest of those draining to the Kerio valley. The river is perennial and approximately 112 km long, and is the main tributary of the larger Kerio River, which feeds Lake Turkana, the world's largest permanent desert lake.

The catchment is characterized by three physiographic regions: the highlands, formed by the Cherangani Hills (forested); the Elgeyo escarpment in the midlands, and the Kerio valley in the lowlands, which is within the Great Rift Valley. The Arror watershed has three main topographic zones which run roughly North-South – the highland plateau, which rises from 2,800 to 3,350 m above sea level (masl), the Marakwet escarpment, which ranges from between 1,200 and 1,500 masl, and the Kerio valley, between 900 and 1,500 masl. The Kerio catchment lies to the east and drains into Lake Turkana.

Data sources

The primary data sources for the study included Landsat satellite images, a Digital Elevation Model (DEM), and socio-economic data. Landsat 5 thematic mapper (for January 1986) and Landsat 7

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enhanced thematic mapper (for January in each of 2000 and 2012) with 30 m resolution were used to analyze land use/cover in the catchment. The land use classification system published by Anderson *et al.* (1976) was modified for the study and eight classes were considered: Coniferous forest cover, Deciduous forest cover, Grassland, Bare ground, Riverine and ridge vegetation, Crop land and Wetlands.

The DEM was used to delineate the watershed and determine slopes in the study area. Field surveys and questionnaires were administered to collect information on the causes of land use change and other socio-economic data.

Secondary data included those on climate, soil, Arror River discharge and population, all of which were obtained from the relevant organizations.

Sampling and survey

The target population comprised the residents of the Arror watershed, approximately 10,000 people. Multi-staged cluster sampling was used to select random targets and the appropriate sample size was determined using the formula (Equation (1)) published by Fisher *et al.* (1991).

$$n = Deff^{*} \frac{Z^{*}_{\alpha/2} P(1-q)}{d^2} \tag{1}$$

where; $n =$ Desired sample size; $Z_{1-\alpha/2} =$ Type I error and Z statistic represents level of confidence or the normal distribution critical value for a probability of $\alpha/2$ in each tail. For a 95% confidence level (CI), $Z_{\alpha/2} = 1.96$; $P =$ Proportion of households having knowledge of the conservation of water catchment areas in the watershed (determined from a pilot survey); $q =$ Expected proportion of households who do not have knowledge about water catchment area conservation; $Deff =$ Is the design effect in case of multi-stage cluster sampling (for cluster samples set at a *default* value of 2).

The level of previous knowledge on water conservation practices in the general population was set at 70% after doing a pilot survey. In this case, $p = 0.7$ and $q = (1-p) = 0.3$. The standard parameters of 95% significance (α) and $Z_{\alpha/2} = 1.96$ were chosen.

Inserting these values in Equation (1) showed that the sample size should be 646 households.

The main data collection tool for surveys in the study was questionnaires. Respondents had to be aged 18 years or more and genuine residents of the region. Discussions were also held with key professionals – the county Forest Officer, Agricultural extension officers, Water Resource Management Authority officers, and county environmental officers.

Climate data

Climatic data for the Arror watershed were limited because there is no well-maintained meteorological station. The stations at Kapsowar and Arror, within the study area, collect only rainfall data with numerous gaps. Data from stations at Eldoret, Kitale, Kapsowar Inland Mission (2,286 masl), Chebiemit and Kapcherop (2,270 masl) were also used, as they are close and at altitudes similar to those in the study area. Eldoret station is approximately 100 km south and at 2,084 masl, at latitude 0° 32′ N, longitude 35° 17′ E.

The nearest neighbors (NN) and inverse distance weighting (IDW) methods were used to impute the missing data in the databases and reduce topographic effects. In order to improve data quality and increase the effective rain gauge density, spatial interpolation was carried out using IDW, and three additional, dummy gauging stations were created at Kapyeko, Kipkunurr and Koitilial.

Temperature data for 1985 to 2012 were extrapolated from the neighboring Eldoret, Kitale and Chebiemit stations to create dummy stations. Four such, similar to the rainfall stations, were created

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and provided synthetic daily temperature data in the range 12 to 37 °C. Time series data for daily maximum and minimum temperatures (Tmax and Tmin, respectively) were generated using the temperature lapse rate method of Minder *et al.* (2010).

In the IDW method used to develop time-series rainfall data, sample weights were inversely proportional to the distance from the point estimated. All stations with long-term data sets were used in the algorithm to determine the weighted rainfall for the new station. Missing portions from any station's dataset were filled with these data series using Equation (2):

$$P_x = \frac{\sum_{i=1}^{N} \frac{1}{d^2} P_i}{\sum_{i=1}^{N} 1/d^2} \tag{2}$$

where P_x = estimate of average basin rainfall (1986–2010), p_i = rainfall values of rain gauge i, d = distance from gauge i to the centroid of the basin, and N = number of gauges.

The variables were rainfall (mm/month), and the mean minimum and maximum temperatures per month. The location of each variable was identified using cell coordinates from (0, 0) in the lower left, and increasing upward and to the right (New *et al.* 1999). The characteristics of a virtual station centroid to the basin lie somewhere between those of the Kapsowar and Arror stations with respect to rainfall, number of wet days and temperature, and use of the mean from those two removed bias, giving the generated centroid characteristics mid-way between those of the other two. The average records from Kapsowar and Arror were used to calculate the parameters in the weather generator (.wgn) file, which was created with the WGNmaker4.xlsm tool (Wang *et al.* 2014), an Excel macro that calculates the weather statistics for SWAT models. The inputs to the tool included daily datasets for rainfall (mm) and temperature (max and min).

Hydrologic data

The catchment has two river gauging stations (2C05 and 2C18) as shown in Figure 1. Station 2C05 had a longer period of record (1961–1992) than 2C18 (1982–1992), and the latter contained more daily flow data gaps. A plot of mean annual river flows against time also showed that annual flows at 2C18 were much lower than those at 2C05. This was expected as fourteen irrigation canals take water upstream of 2C18 but downstream of 2C05.

Many gaps had to be filled in the discharge dataset. Missing values were estimated by interpolation or averaging for some years, but, for extended gaps, infilling requirements depended largely on the gap length, the different season(s) and the availability of hydro-meteorological data from neighboring areas. The technique applied factored in gaps with different durations and in different seasons (wet and dry), the latter based on historic rainfall time series. To synthesize the missing discharge data for the Arror River, discharge measurements from neighboring river gauges and point rainfall measurements in the catchment were used. In response to the catchment's rainfall pattern, the annual discharge records matching with the period were separated into low (dry) and high (wet) flow seasons. The threshold values adopted were the long term mean daily runoff values for the basins concerned. Discharge measurements were then estimated using the corresponding rainfall data. The observed discharge data from 2C18, at the catchment outlet, were used to calibrate and validate the SWAT model.

SWAT modelling

The ArcSWAT 2012 model is a physically based, spatially distributed, continuous time, hydrologic model, developed by the USDA-Agricultural Research Service, and Texas A&M University (http://swat.tamu.edu). It is applied at basin level to simulate various hydrologic, climate and land use

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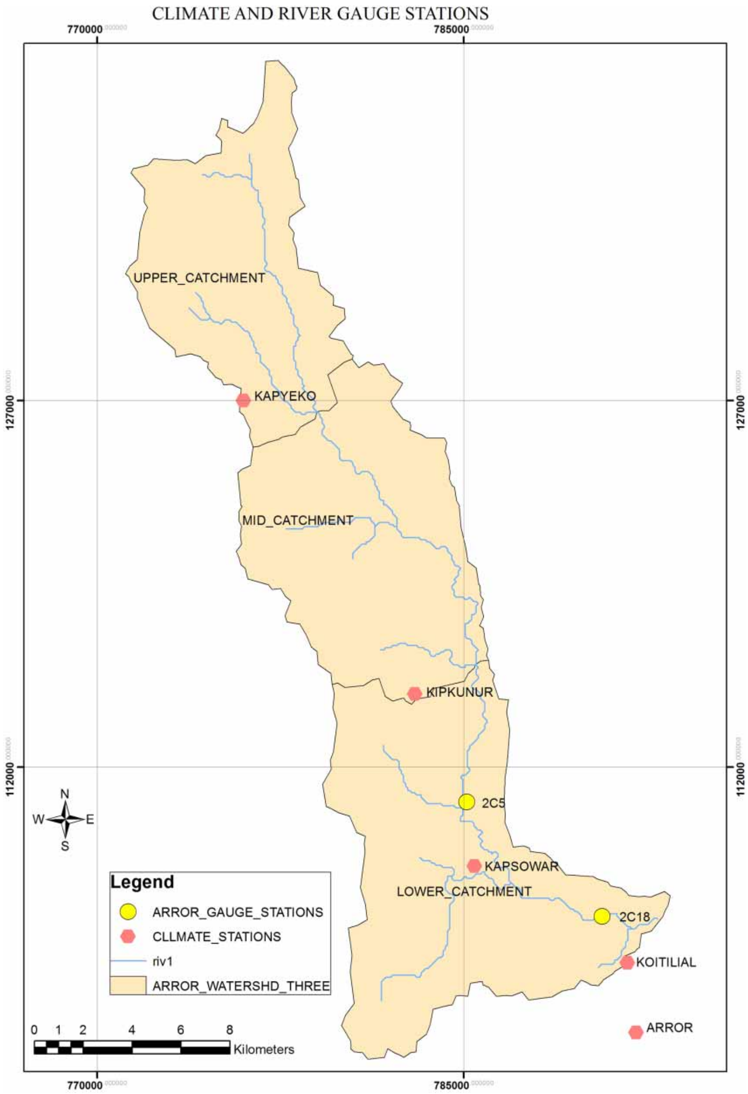

Figure 1 | Locations of climate and river gauging stations in the watershed.

change processes. Its output can be used to assess the impact of vegetation growth, land use and sedimentation on water quantity and quality (Arnold & Allen 1996).

GIS interfaces (e.g. ArcGIS, Open Map, Grass, etc.) are attached to SWAT to enable basin sub-division. The sub-basins constitute hydrologic response units (HRUs), which are categorized with regard to land use, soil type and slope class (Arnold *et al.* 2012). SWAT has been used worldwide for hydrologic studies in relation to managing water and land resources.

The SWAT model integrates hydrologic, sedimentation, weather, plant growth; erosion and pesticide functions, which enable it to simulate hydrologic processes and land management operations. Under the hydrologic function, the water balance in a catchment is calculated using Equation (3) (Arnold & Allen 1996).

$$SW_t = SW_O + \sum_{i=1}^{t}(R - Q - ET - P - QR) \tag{3}$$

where SW_t is the soil moisture at time t (mm), SWo is the initial soil moisture (mm), and R is precipitation (mm), ET evapotranspiration (mm), Q surface runoff (mm) and subsurface lateral flow (mm), P percolation (mm), and QR return flow (mm).

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A model of the Arror catchment was developed using ArcSWAT 2012 (http://swat.tamu.edu) model. The aim was to simulate the flows in three years – 1986, 2000 and 2012. The three output sets were analyzed and compared, to determine the extent of land use change and its impact on the hydrologic variables, and, subsequently, on environmental flows.

ArcSWAT 2012 model set-up

The SWAT model was developed using the DEM, land use/cover map, and soil and meteorological data, to create sub-basins and, subsequently, the HRUs. This was done after processing the input data. The DEM was the first uploaded and used to delineate the 284.8 km^2 catchment. A threshold area of 5.6 km^2 was used in definition of stream network and sub-basin outlets, and the study area divided into 21 sub-basins. After this the land use and soil data were uploaded and overlaid on the DEM. The slope derived from the DEM was divided into five classes with 5% interval values of 0–5%, 5–10%, 10–15%, 15–20% and >20%, to accommodate the various gradients in the catchment. The classification was also was based on the Agriculture Act, Cap. 318 of 1986, which prohibits the cultivation of land with more than 20% slope (Republic of Kenya [ROK] 2012). The slopes assisted in defining the HRUs and the drainage areas.

In generating the HRUs, a threshold of 10% of the land use over the sub-basin area was used. Soil class over land cover area was defined at 10% and the slope class over soil area at 10%. This meant that land uses occupying less than 10% of a sub-basin were eliminated and HRUs were created for land use covering more than 10% of it. The same holds for soil and slope layers. Use of the threshold percentage avoids the generation of minor HRUs and enhances model computation efficiency (Masih *et al.* 2011).

To develop the weather aspect of the model, the daily rainfall data, and temperature minima and maxima for the 28-year period 1985 to 2012 were input to the model's weather database. In the ArcSWAT 2012 model, the weather station nearest the centroid of each sub-basin is taken as the precipitation location in the simulation. Schuol & Abbaspour (2006) note that unrealistic weather data are generated by Arc SWAT 2012, if a weather station assigned to a sub-basin has only a few measured or many erroneous values. According to Grimes & Pardo-Igúzquiza (2010), the benefits of geostatistical analysis for rainfall include the ease of estimating areal averages, the estimation of uncertainties and the possibility of using secondary information like topography. In the NN method, the rainfall stations closest to those with missing data were used to fill in the gaps.

The ArcSWAT 2012 model simulation was set up using a two-year warm up period (1985 and 1986).

ArcSWAT 2012 model calibration and validation

During calibration, input parameters were varied, and the coefficient of determination (R^2) and Nash-Sutcliffe Efficiency (NSE) were used to determine the best parameter values (Nash & Sutcliffe 1970). The parameter value with the highest R^2 and NSE was considered the best. In addition, a reasonable relation between the simulated and observed mean flows was considered in optimizing parameters used for calibration, i.e. Soil Conservation Service runoff curve number II, groundwater recharge to the deep aquifer (Rchrg_dp), and the threshold depth of water in the shallow aquifer required for return flow to occur in mm (GWQMIN).

The model was calibrated using annual discharge data from gauging station 2C18, at the catchment outlet. The initial 15 years (1985–1999) were used for calibration and the rest (2000–2012) for validation.

Manual calibration was done using actual discharge data, to tune the model. The aim was to make the simulated outflow close to the observed outflow; this was to be achieved by adjusting values of surface runoff and base flow contribution to the reach with reference to the land cover values. The

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portion of land occupied by agricultural activities was of key importance in calibration, parameters representing soil and moisture conditions required for crop growth were adjusted (Arnold *et al.* 2012).

After each calibration run, the observed and simulated flows were compared at annual time steps for the first 15 years. The values of R^2 and NSE were then checked to assess the model's performance. Every calibration run was followed by validation.

RESULTS AND DISCUSSION

Land use changes between 1986 and 2012

The findings, by land use class, are shown in Table 1.

Table 1 | Land cover classes for 1986, 2000 and 2012

Land cover classes	1986 Area (km^2)	2000 Area (km^2)	2012 Area (km^2)
Deciduous forest/indigenous	76	44.2	67.9
Coniferous forest	120.6	117.0	109.2
Grassland	36.7	8.5	13.2
Bare ground	5.7	45.1	0.3
Wetland	14.1	0.1	5.1
Ridge-riverine vegetation	0.0	7.8	16.8
Crop land	31.9	62.4	72.5

From the above, it is evident that changes have occurred. The land use change analysis was done using 1986 as the base and 2012 as the final year. Major changes occurred in both the deciduous and coniferous forest cover over the twenty-six year period.

A gradual increasing trend was evident in crop land cover due to increased agricultural activity, mostly farming; this probably arose from increasing food demand. Between 1986 and 2000 some 30.5 km^2 were converted to crop land, a change of 10.7% of the total watershed area, with a further 3.5% to 2012. The area of wetland decreased by 4.9% (14 km^2) between 1986 and 2000. A sharp decrease in grassland cover – 9.9% from 1986 to 2000 – was also registered due to increased crop land area; between 2000 and 2012, however, grassland cover increased by 1.6%.

Causes of land use change in the Arror watershed

There have been many changes in the Arror catchment area. The main causes noted by respondents were: tree cutting (58% of respondents), encroachment (51%), cultivation along the river banks (43%) and overgrazing (20%). These explain the decrease in both deciduous and coniferous forests from 1986 to 2012.

The main factors contributing to deforestation in the catchment were: insecurity in the Kerio Valley (including downstream of the Arror basin) driving people to move from the valley to the escarpment; landslides near the escarpment forcing them to move further into the Kipkunur and Embombut forest reserves; the issuing of permits for grazing in the forest glades, in 1914 and 1922, and; the dependence of the Dorobo clans in Marakwet on gathering and hunting in the forest since time immemorial. As populations have increased, lifestyles have changed to farming, putting more pressure on the land. Decreases in soil infertility have been caused by poor land management on the settlement schemes near Kipyeko. The farmers have, therefore, preferred to move into the forest for fertile land and the

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establishment of public institutions. This has led to the establishment of 56 schools there, and several shopping centers, which are progressively expanding and encroaching into the forest land.

Land exchange for the establishment of the district headquarters at Kapsowar town in 1994 led to excision at Chebara and Kapkoros forests, which affected flows in the Arror River.

Impact of land use on stream flows in the Arror River

The ArcSWAT 2012 model was used to assess the impact of land use on flows in the Arror watershed, after calibration and validation. The calibration results were 0.8 and 0.9 for R^2 and NSE, respectively, while those for validation were both 0.8. This showed that the model is capable of providing a good estimate.

The percentage land use changes in the Arror catchment over the 26-year period are shown in Table 2. In general, there was an increase in the proportion of agricultural land, caused by the reduction in forest, grass and bare lands to provide space for farming. This can be attributed to the increase in population and consequent increased demand for food, leading to increased farming activity. The majority of respondents noted that the causes of changes in the region were tree cutting and encroachment.

Table 2 | Percentage change in land use for the period 1986–2012

Land use	1986–2000 (%)	2000–2012 (%)	1986–2012 (%)
Deciduous forest	−11.2	8.3	−2.8
Coniferous forest	−1.3	−2.7	−4.0
Grassland	−9.9	1.6	−8.3
Agriculture	10.7	3.6	14.3
Bare ground	13.8	−15.7	−1.9
Wetland	−4.9	1.8	−3.2
Ridge/riverine	2.7	3.2	5.9

The change in land use over time has had an impact on watershed hydrologic processes. This was confirmed by the varying amount of discharge in the 3 one-year regimes (1986, 2000 and 2012). Using the same sets of climate, soil and slope data, and altering the land use in the model, showed that land use changes affect river flows. The 1986 pattern of land use, when applied in the model, yielded an average flow rate of 2.0 m^3/s, with 2.5 m^3/s for 2000, and 1.9 m^3/s for 2012 – i.e., the model showed the highest runoff for the year 2000 (Figure 2). Flow variations can, therefore, be attributed mainly to land use changes. The discharge increase in 2000 could arise from deforestation and rendering the land bare, thus increasing runoff in critical areas of the catchment. This is supported by the

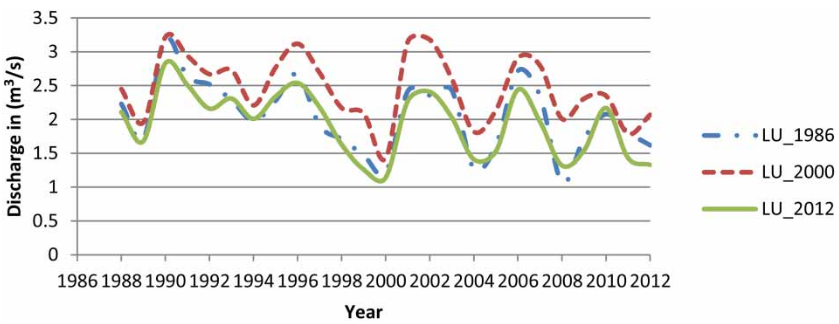

Figure 2 | Simulated Arror River flows for 1986, 2000 and 2012. LU: Land Use.

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study results showing that the percentage forest cover changing with time, 1986 having 69.0 cover, 2000, 56.6, and 2012, 62.6%.

The average monthly flows for the three regimes, based on actual land use and climate for those years, is shown in Figure 3. The flows follow the same trend, with the lowest at the beginning of the year, a peak mid-year, and subsequent decrease towards the year end. The results also showed that the highest peak and lowest minimum flows occurred, in the model, in 2000, which had the lowest proportional forest cover. It appears therefore, that conversion of forests to agriculture and grassland in the basin, reduced dry season flows and increased peak flows, leading to greater water scarcity at critical times and exacerbating hill slope erosion. This latter occurs because reduced vegetation cover reduces infiltration, increasing runoff and reducing base flow. High runoff can cause floods and landslides, while low dry season flows can cause drought.

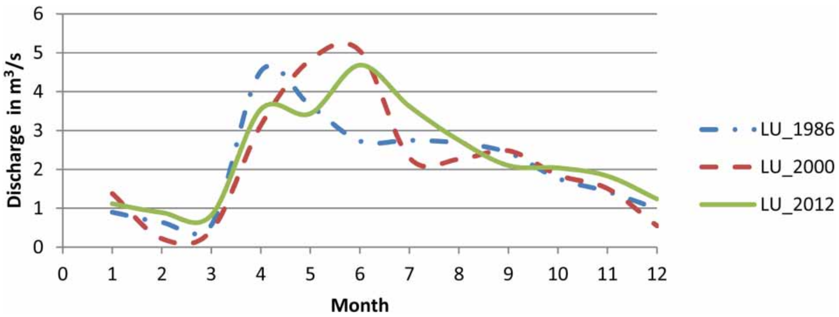

Figure 3 | Average monthly flows as modeled for 1986, 2000 and 2012.

It was also noted that the period of peak flow moved to the right over time, with 1986, 2000 and 2012 having peaks in April, May and June respectively. This may show that the annual seasons have been changing, possibly because of land use changes and, partially, climate change.

CONCLUSION

There have been many land use changes in the Arror catchment. Major changes have occurred in both deciduous and coniferous forest cover over the 26-year study period. In parallel with the decline in forest cover has been an increase in the proportion of agricultural land. The causes include tree cutting, and agricultural and settlement encroachment, accelerated by increasing population pressure. The land use changes have had an impact on watershed hydrologic processes such as river flows.

Proper management of the catchment should include increases in forest cover through afforestation and agroforestry programs. This will, in turn, lead to higher minimum and lower maximum flows, so that water is available in more suitable quantities throughout the year. In the long run this should reduce the occurrence of floods, landslides, etc., as well as increasing infiltration into the soil, which will conserve it and boost base flow. There is a real need to improve watershed management to ensure environmentally sustainable flows.

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