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Hydrological Response to Predicted Land Cover Change in the Upper Shire River Catchment, Malawi

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ABSTRACT The problem of water shortage and competition is getting increased attention in the field of water management. Good quality ground and surface water may become too scarce to allow for sustainable use for various functions. With increasing human activities, it is important to understand interactions between hydrological regimes and associated land use, and land cover change in the catchment. This paper reports the use of the Soil and Water Assessment Tool (SWAT) model to develop an approach for modelling and evaluating potential impacts from future land use and land cover change on the annual and seasonal water balance of the Upper Shire River catchment in Malawi. The results indicated that by 2020, groundwater recharge in the Upper Shire sub-catchment would decrease by 21–31 percent and stream flows by 35.7 percent due to the future reduction of woodlands and increase in agricultural land. The proposed approach provided a quantitative description of the main environmental impacts vis-à-vis hydrological processes arising out of rural land-use change at the river-catchment scale, which can be used when planning for sustainable land and water resources management.

INTRODUCTION

Precipitation and land hydrological processes maintain the water balance in a river basin. Land surface performs a role in the hydrological cycle, as water availability is generally a consequence of precipitation redistributed into evaporation, run-off and soil moisture storage (Dolman and Verhagen 2003). The largest part of precipitation passes over the land surface or drain through the soil and bedrock to translate into river flows. The spatial heterogeneity associated with land cover, soil properties and localized precipitation influences soil moisture and surface fluxes. Land cover change and the effects of land management on the hydrological response of a catchment are most likely where the change alters the surface characteristics of a basin. The degree and type of land cover influences surface run-off and the rate of infiltration, and consequently the rate of ground water recharge (Calder 2002; Dingman 2008). Changes in these hydrological variables may have implications for water resources.

The relationship between land cover change and hydrology is complex, with linkages existing at a wide variety of spatial and temporal scales. However, land cover change unquestionably has a strong influence on global water yield (Frenierre 2009). Land cover and use directly influence the amount of evaporation, groundwater infiltration and overland runoff that occurs during and after precipitation events. For example, the conversion of vegetation such as tropical forest or savanna to grassland disrupts the hydrological cycle through reduced evapotranspiration (ET) and increased long-term discharge (Zhang et al. 2001; Costa 2003). Forests have a higher interceptive potential than grassland, arable land lower than grassland. Conversion to cropland tends to increase water yield compared to native vegetation although this varies with the crop and the season while manmade surfaces such as tarmac have the lowest interceptive potential (Haslam 1987).

Comprehensive knowledge of land use dynamics is useful for reconstructing past land use and cover changes and for predicting future changes. It may help in elaborating sustainable management practices aimed at preserving essential landscape functions (Hietel et al. 2004). Though many land use models have been developed using GIS (Almeida et al. 2008; Xia and Xiaoping 2008), a simple approach was taken for scenario analysis of this study due to limited data access. Scenario analysis is gaining widespread acceptance among decision-makers as a practical tool for addressing uncertainty about the future. Scenarios, as defined by the Intergovernmental Panel on Climate Change (IPCC 2001), are "plausible and often simplified descriptions of how the future may develop based on a coherent and internally consistent set of assumptions about driving forces and key relationships." In the realm of natural sciences, this is accomplished by using a combination of land-use change and process models to develop an artificial representation of the physical manifestations of scenario characteristics, and to establish a multi-disciplinary framework within which scenario characteristics may be analyzed (Turner et al. 1995).

The condition of water resources in the Upper Shire River sub-catchment (USRs) in Malawi has been affected adversely by rapid changes in land cover over the last two decades. Large areas in the Shire River catchment in Malawi have suffered considerable land cover changes since the mid 20th Century. The major driving forces are related to human population increase and rainfall variability (Malawi Government 1998). The high population growth rate has translated into rapidly increasing demands from land in terms of food, shelter, energy (fuelwood) and construction materials. Agricultural crops now replace some of the woodlands, while the grass-covered dambos have been either overgrazed or cultivated and are left bare. This trend is most likely to continue as evidenced by current agricultural practices and population growth[1] (NSO, 2008). The land cover in the catchment is dominated by subsistence agriculture and savanna woodland. Summaries of the changes in land cover distribution, showing the percentage of land cover for 1989 and 2002 have been discussed in Palamuleni (2009).

The potential to predict the effects of future land cover changes is very important for future use and management strategies in the USRs. Therefore, the objective of this study is to simulate the likely changes in response to continued deforestation of rural Malawi. To predict future flow of the USRs, three scenarios were examined. The first is continued land cover change at current trends; the second accelerated change associated with extensive deforestation; and third is the reduced land cover change due to sustainable management and reforestation.

METHODOLOGY

Figure 1 shows the Shire River basin in the southern part of the Great East African Rift Valley system and is the outlet of Lake Malawi. It is a tributary of the Zambezi River. The entire catchment area is ~18,000 km^2 and consists of the upper, middle, and lower sections. The Upper Shire river catchment is between Mangochi and Matope, with a total channel bed drop of about 15 m over a distance of 130 km. The focus of this study is the uppermost reach from Mangochi to Liwonde, which is almost flat at 465–600 m above mean sea level over a distance of 87 km. It forms a catchment area of ~4,500 km^2, located between latitudes $14^0$20'S; $15^0$12'S and longitudes $34^0$59'E; $35^0$30''E.

Mapping of land cover change utilized available 30-m grid spatial resolution snapshots of Landsat TM and ETM, for the years 1989 and 2002, respectively. Image pre-processing was carried out using techniques described in Jensen (2005) and Lillesand et al. (2004).

The topography of Shire catchment was mapped from the recently released Shuttle Radar Topography Mission (SRTM) data (USGS 2006). Soils data were extracted and computed from the UN/FAO digital soil map of the world soil map (Scale: 1:1,000,000) (FAO/UNESCO, 2003). Daily discharge readings of the Shire River at two stations were obtained from the Hydrology Department of the Ministry of Water Resources of Malawi for the period 1976–2006. There are only two flow-gauging stations on the Shire river within the study area, one at the inlet to the valley at Mangochi (1T1), and one at Liwonde (1B1), taken as the outlet (Fig. 1). Climatic input data (including daily precipitation, maximum and minimum air temperature, wind speed, and relative humidity) were collected from meteorological office based on their spatial distribution in the study catchment (Fig. 1).

The mapping of land use and land cover change over time began with mapping the 2002 satellite imagery, then looking back into history to map the 1989 satellite imagery. The image dates used were July 1, 1989 and May 25, 2002. Within the constraints of a limited number of suitable images in archive, a strategy for selecting Landsat imagery for development of land cover database for the Upper Shire river catchment was governed by cost-free available multitemporal images, vegetation phenology, and image quality (cloudiness, haze) (Palamuleni 2009). Besides, both images preceded La Nina episodes and the effects of differences in acquisition time were therefore acceptable (SADC: Drought Monitoring Centre 2004). As such, vegetation characteristics appeared comparable since similar rainfall

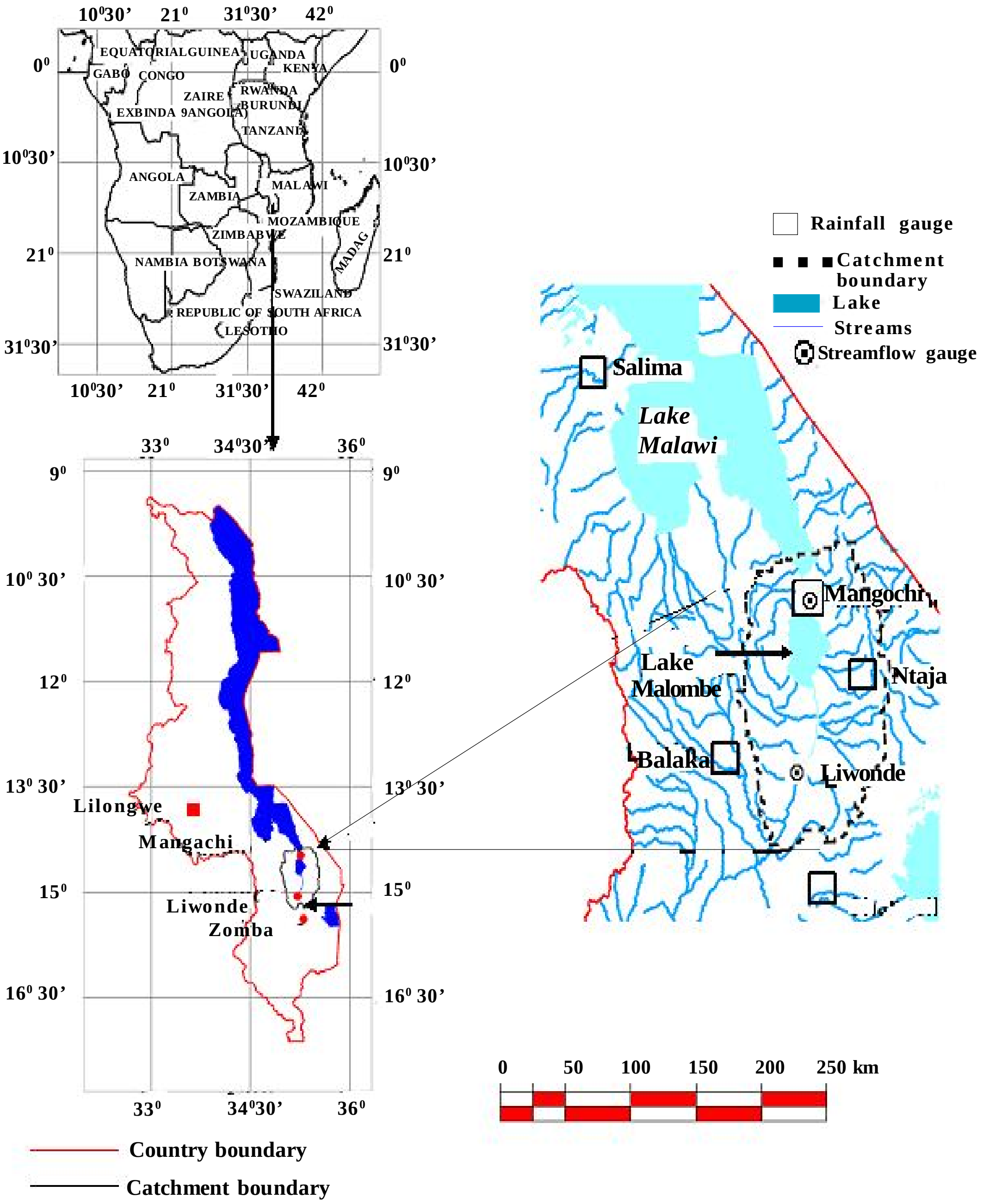

Fig. 1. Location map of Shire River catchment, Malawi

conditions preceded both images. Supervised maximum likelihood digital image processing was employed by defining training sites, on the image, which are representative of each desired land cover category (Jensen 2005).

The soil and water assessment tool hydrologic model is a physically-based semi-distributed geospatial hydrologic model. The model uses remote sensed and ground observation data (soil, land cover, rainfall, and evaporation), and digital elevation data sets describing the land surface to calculate the basin hydrologic water cycle (Arnold and Fohrer 2005). It provides a continuous simulation of stream flow, on a daily time step. Geographic information system (GIS) data for topography, soils, and land cover were used in the AVSWAT, an ArcView-GIS interface for the SWAT model (Di Luzio et al. 2001). A digital elevation model (DEM) defined the topography of catchment. The generated stream flows were routed down the stream, guided by the terrain of the basin as defined by the DEM data. The soil data is required by the SWAT to define soil characteristics and attributes. The land cover data provides vegetation information on ground and their ecological processes in land and soils. For purposes of compatibility in SWAT, the USRs land cover codes were converted to the SWAT land cover/plant codes (Table 1). The catchment was divided into several sub-basins based on the DEM, stream network and outlets, and each sub-basin was split into several hydrological response units (HRUs) based on the land cover and soil data. Two simulations, annual and monthly streamflow from 1977 to 1981 were made for the catchment, one with the 1989 land cover data and the other with the 2002 land cover data. Observed daily rainfall and temperature data were needed to simulate streamflow, which was compared with the observed streamflow during calibration and validation processes routed at Liwonde gauging station (Fig.1). Calibration was done manually by varying the model's most sensitive parameters. The sensitive model parameters are SCS runoff curve number (CN2), soil evaporation compensation factor (ESCO), soil available water capacity (SOL_AWC), soil depth (SOL_Z), surface runoff lag time (SURLAG), saturated hydraulic conductivity (SOL_K), baseflow alpha factor (ALPHA_BF) and ground water ‘‘revap’’ coefficient (GW_REVAP) (Palamuleni 2009).

Table 1: Spatial distribution of land cover classes and SWAT land cover class codes for 1989 and 2002

LCCS Classi-fication	*SWAT Land/ Plant cover classes*	*1989*		*2002*	
		Area (Ha)	*Per cent*	*Area (Ha)*	*Per cent*
Fresh water	Water	40 573	8.3	37 100	7.6
Built-up areas	Residential medium density	58 835	12.0	5 775	1.2
Culti-vated/ grazing	Agri-cultural Land Generic	110 874	22.6	200 570	40.9
Marshes	Wetland	4 982	1.1	24 412	4.9
Savanna shrubs	Range-land range brush	190 795	38.9	110 495	22.6
Woody open	Forest mixed	37 446	7.6	36 629	7.5
Wood closed	Forest Decious	46 595	9.5	75 119	15.3
Total		490 100	100.0	490 100	100.0

Each parameter was varied while holding the other parameters constant until the highest correlation between the simulated and observed was obtained. Care was taken when varying the parameters to make sure that the final basin parameters were within actual ranges. The resulting streamflow was compared with observed values qualitatively and quantitatively using plots and coefficient of determination, R^2, respectively.

In terms of scenario generation, as a first test, two extreme limiting scenarios were considered – total deforestation and total forestation. The modelling process was carried out to assess influences on run-off components and total water yield in response to these bounding conditions. Most likely changes to land cover are conversion from rangeland and forest to agriculture in a land-degradation (pessimistic) scenario, and conversion from agricultural land to rangeland and forest in a land-conservation (optimistic) scenario. Changes to all three of these land cover types have influences on catchment hydrology. Urbanisation equally affects hydrological processes. However, it was excluded from scenario analysis, as it constitutes a small fraction of the total area, and in Malawi, still a small area of change. For the second stage scenario modelling, a range of scenarios were considered, in which fractional changes were made to these three land cover classes for the pessimistic and optimistic trends.

Table 2: Land cover hypothetical scenarios

Scenario	*Description*
Business as usual (baseline)	Forests are reduced in the lower and upper escarpments within the catchment in favour of transitional woodland-shrub; there is transformation of savanna shrubland areas into cultivated and grazing land; and there are major increases in grassland areas.
Land degradation (pessimistic)	Assumes accelerated land cover change with extensive deforestation. significant fractions of forest and savanna shrubland areas are transformed into the category agricultural land, which includes subsistence agricultural areas, transitional woodlands and sparsely vegetated areas
Land conservation (optimistic)	Assumes creation of a greener environment through management and re-forestation, involves the conversion of potentially vulnerable areas (e.g. subsistence agricultural land and lower escarpments) into forest and savanna woodlands.

Land-use changes are driven by global change processes, especially by markets and political reforms and constrained by the given natural characteristics and socio-economic conditions of a region. This complexity gives rise to a wide range of approaches that range from extreme land-use changes such as total deforestation of a watershed, to the development of models that consider regional socioeconomic aspects. In this study, simple hypothetical scenarios were set considering the current land use trend of the study area as tabulated in Table 2.

The objectives of the study were to identify the change of land cover pattern in two periods 1980s and 2000s through two land cover maps for the years 1989 and 2002 representing each period, then use the SWAT hydrologic model to evaluate the relative hydrologic consequences of anticipated future landscape characteristics. The SWAT model was run separately with the reclassified land cover datasets (Table 1) of 1989 and 2002 as the only variables. Rainfall and evaporation data of 5 years 1977–1981 was used during the simulation. By holding rainfall, evaporation, and soils data sets constant, the analyses isolated the impacts of land-use change, but did not account for the sensitivity of those impacts to variable climatic conditions.

Simulations were performed using three scenarios, which were compared to the baseline case. The 2002 land cover data was used as a base data and scenarios of the future land use and land cover were developed (Table 2). SWAT model was setup for each landuse and land cover change scenario. Absolute and relative changes in annual volumes of surface flow, baseflow and total water yield were calculated for each scenario. Average annual and monthly outflows simulated at the catchment outlet for the various change scenarios were then compared to the baseline case. For the purpose of this study, negative impacts are considered to be increases in surface runoff, streamflow discharge, and decline of baseflow volume.

RESULTS AND DISCUSSION

The Shire River catchment represents an area that has undergone remarkable land-cover change. Classification of land cover in the Upper Shire river catchment categorized eight major groups namely: woody closed, woody open, savanna shrubs, grasslands, marshes, cultivated or grazing areas, built-up areas and fresh water (Palamuleni 2009). The spatial extents of the classified land cover classes indicate marked change in land cover categories between 1989 and 2002. Savanna shrubs and woody open areas had decreased in extents from 23.2 percent to 19.9 percent and 28.7 percent to 11.2 percent respectively. Rapid increasing demands from forest resources for food, shelter, energy (fuel-wood) and construction materials contributed to the decrease in woodlands. This trend has also been observed by Jumbe and Angelsen (2007), who established that the demand for forest products especially firewood is high because Upper Shire River catchment is located close to urban cities of Blantyre and Zomba. Conversely, there was an increase of 4 622 ha for cultivated/grazing areas, which can be attributed to expansion of subsistence agriculture. A study of the two land cover analysis shows that the increase in cultivated or grazing land occurred mainly at the expense of savanna shrubs, woody open areas and built up areas. Cultivated or grazing areas expanded by 1 618 ha from previously woodland areas; 1 671 ha from previously savanna shrubs region; and 1 333 ha from other classes (built-up areas, grasslands and marshes). The clearing of natural vegetation and the increase in agriculture has resulted in severe soil erosion in the catchment. In addition, the deposition of sediments has caused a rise in elevation of the river channel resulting in riverbank backflow during rain seasons. The overflowing water, rich in nutrient sediments originating from high fertiliser run-off from agricultural areas has led to an increase of the catchments' marshlands by 358 percent (Malawi Government 2006).

The SWAT model runoff component was calibrated for a period of 5 years, from 1977 to 1981. The R^2 and values obtained for monthly and daily calibrations were 0.83 (p-value = 0.05; n = 60) and 0.65, respectively (p-value = 0.05; n = 1,808). The model accurately captured the hydrograph rising limbs and peaks but was unable to capture the recession limbs and low flows. Validation was done for 2 years from 1984 to 1985. Similar behaviour of the generated hydrograph as for calibrations was observed. For the monthly and daily, the R^2 was 0.72 and 0.63 (p-value = 0.05; n = 24) and 0.65, respectively (p-value = 0.05; n = 731), respectively.

Predicted hydrologic response in terms of streamflow, baseflow and surface flow were reviewed at the Liwonde station. Future streamflow was calculated under the three scenarios. The results of the two extreme scenarios are compared to the baseline case (Table 3).

Table 3: Simulation results from bounding cases scenarios

	Total water yield (mm)	*Surfae flow (mm)*	*Base flow (mm)*
2002 land cover	397	322	74
Total change to bare soil	463	437	26
Total change to forest	308	195	113

Total deforestation of the entire land surface of the catchment generated a total water yield of 463 mm a^{-1}, compared to 397 mm a^{-1} for the reference scenario. In the case of total deforestation, there is increase in surface flow of 437 mm a^{-1} compared to 322 mm a^{-1}, and a decrease in baseflow of 26 mm a^{-1} in comparison with 74 mm a^{-1} for the reference scenario. Bare areas have a strong effect by promoting rapid run-off and thereby reducing percolation. Ground storage is reduced and surface direct evaporation enhanced. For total forestation, total water yield reduced to 308 mm a^{-1}. In the case of total land cover change to forest, there is a decrease in surface flow from 322 mm a^{-1} to 195 mm a^{-1} and increase in baseflow from 74 mm a^{-1} to 113 mm a^{-1}. Forests absorb most of the precipitation hence there is increased interception, percolation and evapotranspiration, rather than prompt streamflow. Results of this sensitivity analysis show the maximum changes that could be expected from extreme changes in land cover, and hence bounding conditions for the further scenario modelling. The model behaves as expected, with bare land increasing prompt run-off and reducing percolation, and conversely reducing run-off and total yield for full forestation.

Decreasing land under savanna and forest cover, differences in total annual catchment streamflows, baseflows and surface flows were observed. Under the existing land cover (Reference Scenario 2002), the annual catchment streamflow observed was 397 mm, with baseflow making up to 19 percent and the remaining 81 percent from surface flow. In terms of absolute mean annual changes between the reference state and the scenarios, decreasing forest areas by different magnitudes increases surface flow and decreases baseflow and total water yield at the outlet (Fig. 2).

Decreasing savanna areas by 20 percent produces an increase in total water yield and surface flow but a decrease in baseflow. Total water yield increased from 397 mm a^{-1} to 402 mm a^{-1} while surface flow increased from 322 mm a^{-1} to 334 mm a^{-1}. A minor decrease in baseflow has been observed once savanna was decreased by 20 percent. The conversion of savanna into subsistence agriculture does not cause considerable changes in the micro scale basin. This could be attributed to the similarity in the characteristics of both land cover forms under tropical natural conditions. Savanna vegetation has scattered trees and is deciduous during the dry season; thus, a considerable amount of land is exposed, similar to subsistence agricultural land.

A 40 percent decrease in forest yielded total water yield of 397 mm a^{-1}, not different from the reference scenario. However, slight decreases in baseflow ranging from 70 mm a^{-1} to 72 mm a^{-1} have been observed with an increase in the magnitude of deforestation- e.g. 10 percent absolute decrease of 2 mm a^{-1}; 40 percent absolute decrease of 4 mm a^{-1}. Surface flows were observed to be increasing as forestland is reduced. For example, a 40 percent decrease in forest increases surface flow from 322 mm a^{-1} to 327 mm a^{-1}.

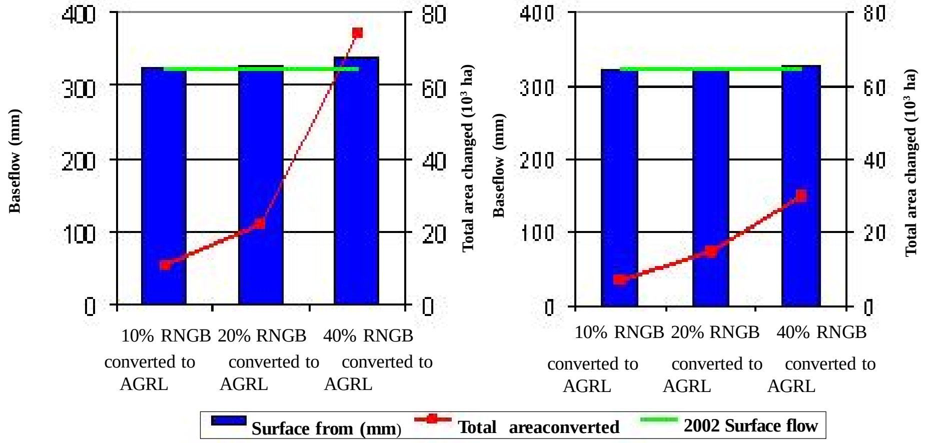

Fig. 2. Surface flow simulation results obtained from land degradation scenarios

Thus, more water is available for surface runoff and less for groundwater recharge. Increased runoff from land conversions from forests to other land uses (e.g. agricultural land) may pose a water quality threat to river systems due to increased soil erosion. These changes result in more water yield and higher basin discharge, a result consistent with previous work (Forher et al. 2001; Ren et al. 2002; Costa et al. 2003; Huisman et al. 2004). For instance, Costa et al. (2003) showed that increase of agricultural land from 30 percent to 49 percent of the Tocatins River watershed (Brazil, 767 000 km^2) led to a 24 percent increase of the mean annual water discharge. Quilbè et al. (2008) found a strong correlation between agricultural land area and water discharge on the Chaudière River watershed in Québec, Canada. An increase in agricultural land to the detriment of shrub land and forest implied an increase of 13.6 percent in runoff over the watershed in spring and fall. These results signifies that runoff is mainly due to strong rainfall events, thus dense vegetation cover such as forest makes a big difference as compared to farmed land regarding rain interception, evapo-transpiration and, consequently, runoff generation.

The predicted relative effect of woodland (savanna and forest) reduction (expressed as percentages) on the annual water balance is compared to that of subsistence agriculture. 10 percent decrease in forest reduces total water yield by 0.7 percent, whereas a 20 percent leads to a decline of water yield by 0.3 percent. Overall, the strongest relative impact can be observed for surface run-off. Decreasing land under savanna cover by 20 percent increases surface flow by 4 percent while decreasing forest by 40 percent increases surface flow by 2 percent. This is due to the increase in land under subsistence farming. The absence of trees and shrubs implies a minimum in surface evapotranspiration and, consequently, a maximum in run-off. The soil is less protected against raindrop impact under agriculture since after harvesting and shortly after sowing, the plants do not cover the soil completely. Depending on the type of product being grown, croplands tend to have a percentage of bare ground even during the peak of the growing season, and may be completely bare prior to planting. In both instances, most of the precipitation that lands on these denuded areas will be discharged directly into the stream channel rather than infiltrating into the soil or evaporating/transpiring from the plant surfaces.

Simulation runs were also performed for land cover scenarios termed *land conservation*, which represents the creation of a greener environment through management and re-forestation. A 40 percent increase in forest increases total water yield from 397 mm a^{-1} to 398 mm a^{-1}. However, the proportion of water infiltrating increases from 74 mm a^{-1} to 225 mm a^{-1} while surface flow decreased from 322 mm a^{-1} to 173 mm a^{-1}. Slight increases in baseflow have been observed with a 20 percent increase in forest, when baseflow increases from 74 mm a^{-1} to 99 mm a^{-1}. Surface flows were observed to decrease as savanna land increases (Fig. 3). Increasing the areas of forest and savanna contributes to decreases of water yield and surface flow and increases baseflow. Predicted increase of forest and savanna by 20

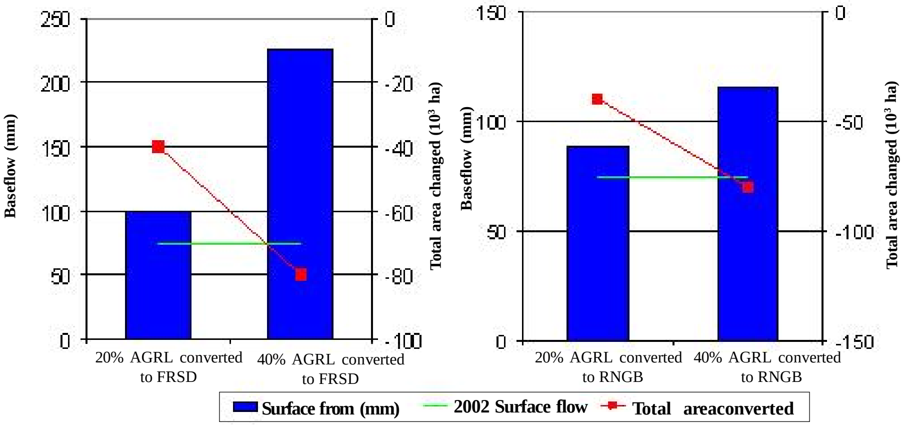

Fig. 3. Baseflow simulation results from land conservation scenarios

percent decreases total water yield to 371 mm a^{-1} while a 40 percent increase decreases water yield to 350 mm a^{-1} compared to 397 mm a^{-1} from the reference scenario. The reduction of the mean annual flow results in a decreasing surface flow during the rainy season with a simultaneous increase in baseflow from 74 mm a^{-1} to 115 mm a^{-1}.

Generally, the strongest relative impact can be observed in the amount of surface flow. Increasing land under savanna cover by 40 percent decreases surface flow by 33 percent, while increasing the savanna area by 20 percent decreases surface flow by 12 percent. Increases of both forest and savanna areas by 40 percent and 20 percent resulted in reductions in surface flow of 50 percent and 40 percent respectively. This is due to the decrease in land under subsistence farming. Baseflow increases and surface flow decreases are due to the higher interception of forests and savanna woodlands in comparison to maize and legumes. The indication of these changes from conversion of agricultural land to forest is the same to those from some previous studies in other regions (e.g., Zhang et al. 2003; Twine et al. 2004; Hu et al. 2004; Guo et al. 2008).

For example, Zhang et al. (2003) found that predicted conversions of pastures to forestry in the Goulburn-Broken catchments, Australia, yield a maximum reduction in mean annual flow is 8 percent for Lake Eildon and 14 percent for Goulburn Weir. Similarly, Guo et al. (2008) in the Poyang Lake basin in China projected land cover change in all farmlands converted into forest, a case representing an extreme when farmers convert their lands for lumber production business. These land-use changes, which account for up to 23.3 percent of the basin area, result in decrease of annual discharge by up to 3.2 percent from the control run. The decrease of surface flow from this conversion may be attributed to the fact that forest land has a higher rate of water loss by large evapotranspiration than agricultural land does and have larger leaf areas to transpire. Large reductions of the river discharge and therefore a considerable increase of water retention in the catchment would occur only in the case of forestation over large areas (Lahmer et al. 2001). Therefore, depending on the magnitude of percentage change in forest cover, the water balance analyses shows that when land under forest vegetation increases, dry season flow increases and wet season peak flow decreases compared to the reference scenario.

CONCLUSION

Land use and vegetative cover play an important role in catchment runoff and streamflow discharge patterns over time, including peak flows. Increased human interventions have caused rapid transitions in land cover, adversely affecting the catchment processes and hydrological cycle in the end. Distributed hydrological modelling offers an efficient solution to evaluate the long-term hydrological changes by allowing quantification of changes in streamflow patterns. Within the USRs, hydrological processes (surface flow, baseflow and infiltration) are largely driven by the nature and density of land cover and the type of land cover over a catchment. Increasing subsistence agricultural areas and simultaneous declines of woodlands will result in increased annual and event surface flow volumes. In general, the simulation results indicate that land-cover changes associated with future development will alter the hydrology of the catchment.

In this study, the applicability of SWAT in different contexts of catchment management has been explored. In particular, the possibility of predicting impacts of land cover changes for deciding on future uses of the Shire River catchment were demonstrated. Hence, parameters potentially sensitive to negative impacts, in this study being: any increases in surface run-off, increases in quick flow and/or declines in groundwater percolation, have been identified. This combination of tools (remote sensing, hydrologic modelling and scenario analyses) provides one of the most powerful approaches to quantify and forecast the relative impacts to ecosystem services, and thus improve our collective decision-making for the future.

RECOMMENDATIONS

The predicted results can be used as a basis for setting priorities for local policy considerations, research for regional planning and water resources management. The results from this research are particularly relevant for Malawi and for other developing countries in formulating, implementing and monitoring strategies for sustainable development. It is recommended that the impact of land cover change could be extended by the consideration of anticipated climate change, its modification of hydrological processes and the feedback on land cover.

NOTE

1. Over the last three decades, population density in the Southern Region of Malawi (Shire River catchment located within this region) has shown an upward trend. The population density is given as 139 people km^{-2}, 105 people km^{-2}, and 85 people km^{-2} in the period 2008, 1998 and 1987, respectively.

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