Journal of Hydrology 486 (2013) 100–111

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Using the Soil and Water Assessment Tool (SWAT) to assess land use impact on water resources in an East African watershed

Tracy J. Baker *, Scott N. Miller

Ecosystem Science and Management, University of Wyoming, 1000 East University Ave., Laramie, WY 82071, USA

ARTICLE INFO

Article history:
Received 7 October 2012
Received in revised form 22 December 2012
Accepted 20 January 2013
Available online 8 February 2013
This manuscript was handled by Geoff Syme, Editor-in-Chief, with the assistance of John W. Nicklow, Associate Editor

Keywords:
Hydrologic modeling
Watershed management
Groundwater
Kenya
Lake Nakuru

SUMMARY

Land cover and land use changes in Kenya's Rift Valley have altered the hydrologic response of the River Njoro watershed by changing the partitioning of excess rainfall into surface discharge and groundwater recharge. The watershed contributes a significant amount of water to Lake Nakuru National Park, an internationally recognized Ramsar site, as well as groundwater supplies for local communities and the city of Nakuru. Three land use maps representing a 17-year period when the region underwent significant transitions served as inputs for hydrologic modeling using the Automated Geospatial Watershed Assessment (AGWA) tool, a GIS-based hydrologic modeling system. AGWA was used to parameterize the Soil and Water Assessment Tool (SWAT), a hydrologic model suitable for assessing the relative impact of land cover change on hydrologic response. The SWAT model was calibrated using observation data taken during the 1990s with high annual concordance. Simulation results showed that land use changes have resulted in corresponding increases in surface runoff and decreases in groundwater recharge. Hydrologic changes were highly variable both spatially and temporally, and the uppermost reaches of the forested highlands were most significantly affected. These changes have negative implications for the ecological health of the river system as well as Lake Nakuru and local communities.

1. Introduction

Forest cover losses can have serious implications for water resources because during rainfall events, interception decreases and soil infiltration rates are exceeded. Such alterations have the potential to cause flashier flows and result in altered flow regimes (Calder, 1993). Rapid land cover and land use changes from dense indigenous forest and plantations to small-scale agriculture occurring in Kenya's Rift Valley can alter hydrologic response within many important watersheds, such as the River Njoro. In addition to helping sustain wildlife populations within Lake Nakuru National Park, a large and increasing human population residing within the watershed boundary relies on the River Njoro to sustain ecological services (Baker et al., 2010; Okoth et al., 2009; Kibichii et al., 2008; Shivoga et al., 2007).

Conversion of natural landscapes for agricultural and urban uses often impacts soil integrity, nutrient fluxes, and native species assemblages. Such changes can affect watershed hydrology by altering the rates of interception, infiltration, evapotranspiration, and groundwater recharge that result in changes to the timing and amounts of surface and river runoff. There is conflicting evidence, however, regarding how forest conversion or afforestation in tropical regions impacts watershed hydrology (Chandler, 2006). Smakhtin (2001) asserts that changes in hydrology are principally due to the importance of timing of such activities. For example, several studies have demonstrated that the establishment of plantation forests in sub-tropical environments resulted in reduced base flow due to increased transpiration rates and subsequent reduction in groundwater recharge (Locatelli and Vignola, 2009). Vegetation removal can result in increased base flows if soil infiltration capacities remain intact (Brüijnzeel, 2004). On the other hand, if vegetation clearing is followed by land use practices that compact soils and expose them to erosion, then decreased percolation to groundwater can result (Bonnell et al., 2010; Chandler, 2006; Zimmermann et al., 2006).

For much of Africa, physical water scarcity is not the greatest limiting factor for access to water; rather it is economic scarcity that results from lack of investments in water infrastructure and management (Braune and Xu, 2009; Hanjra and Gichuki, 2008; CA, 2007). Poor water quality and decreased water quantity can result from increased demands on available resources by multiple competing water uses, lack of infrastructure, and lax water law enforcement, among many other factors. Poor water quality or lack of adequate quantity can negatively affect human health (in particular child mortality), economic production, and severely impact the sustainability of ecosystems supported by water resources

* Corresponding author. Current address: Environmental Studies, The Richard Stockton College of New Jersey, 101 Vera King Farris Dr., Galloway, NJ 08295-9441, USA. Tel.: +1 609 652 4611; fax: +1 609 626 5515.

E-mail addresses: dr.tjbaker@gmail.com (T.J. Baker), snmiller@uwyo.edu (S.N. Miller).

0022-1694/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jhydrol.2013.01.041

(Mogaka et al., 2005). In some cases, feedbacks between human activities, water use, and ecosystem health lead to degradation of water resources for human consumption and other uses, also resulting in water scarcity.

Groundwater is a key water resource throughout Africa, with perhaps as much as 75–80% of the rural population relying on it as their primary or only water source (Braune and Xu, 2009; Calow and MacDonald, 2009). Groundwater has long been considered an important buffer for rural communities throughout Africa in times of low rainfall or drought because groundwater storage can often be greater than the annual recharge (Braune and Xu, 2009; Calow et al., 1997). In regions such as Kenya's Rift Valley, where groundwater and streamflow are inextricably linked to one another (Ayenew and Becht, 2008; McCall, 1967; McCall, 1957), changes that impact surface flow can have cascading negative effects on groundwater resources as well (Brüijnzeel, 2004). Slow complex recovery times for groundwater resources pose additional challenges when trying to generate management plans for overall water resources and supplies (Calow et al., 1997). Changes to a river's hydrologic regime, therefore, have the potential to significantly disrupt both human and ecological systems.

The Mau Forest Complex is one of five major water towers in Kenya, the others being Mt. Kenya, the Aberdere Range, Mt. Elgon, and Cherangani Hills. Decreasing forest cover has been the cause of concern in recent years (Akotsi et al., 2006; Krhoda, 1988) and there are implications for water resources as a result of widespread and conversion of forests to small-scale agriculture and pasture (Baldyga et al., 2007). While deforestation estimates of the Mau Forest Complex are varied, there is no dispute that conversion of forests to small-scale agriculture has occurred in recent years and continues. Research shows that at least one-quarter of the forested areas within the Likia forest portion of the Mau, which is home to the River Njoro headwaters, have been converted to managed pastures and small-scale agriculture (Baldyga et al., 2007).

Anecdotal evidence collected at stakeholder meetings in 2003 and 2004 by Lelo et al. (2005), along with field observations, suggest that the timing, duration, and overall discharge in the River Njoro have changed. While there are few long-term datasets available to assess changes in water resources in small local watersheds in Kenya, several previous studies showed promising results using Soil and Water Assessment Tool (SWAT) as a method to increase understanding of watershed response to land use change. This project seeks to determine whether the observed land cover changes within the River Njoro watershed can be causally linked to hydrological alterations using the Soil and Water Assessment Tool (SWAT). Coupled with historical land cover and land use information, an assessment can then be presented as to how domestic water sourcing among surface water and groundwater sources has changed since 1986 and implications this may have for water borne disease incidence.

2. Study area

The River Njoro watershed is located in the southwestern portion of Rift Valley at 0°30′ South, 35°, 20′ East (Fig. 1). The river is approximately 50 km in length with an estimated 272-km^2 contributing source area and originates on the Eastern Mau Escarpment at approximately 3000 masl. The River Njoro winds through forested and agricultural lands before serving several

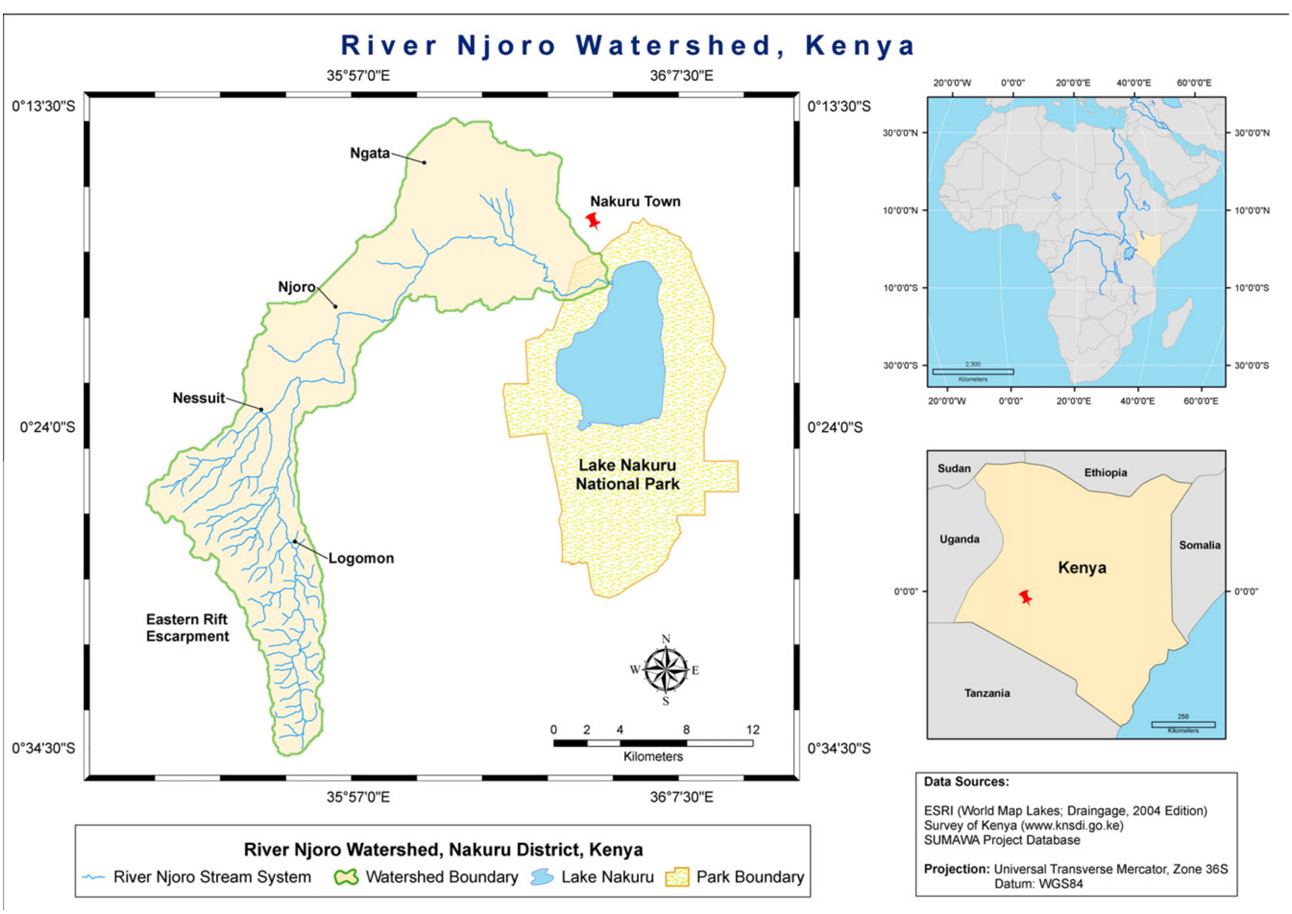

Fig. 1. River Njoro watershed location within Kenya.

Table 1
SWAT surface runoff results indicating no change in runoff on a monthly or annual basis when modifying percent land cover.

Month	+20% Q (mm)	+15% Q (mm)	+10% Q (mm)	+5% Q (mm)	−5% Q (mm)	−10% Q (mm)	−15% Q (mm)	−20% Q (mm)
1	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
2	5.12	5.12	5.12	5.12	5.12	5.12	5.12	5.12
3	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
4	1.62	1.62	1.62	1.62	1.62	1.62	1.62	1.62
5	3.37	3.37	3.37	3.37	3.37	3.37	3.37	3.37
6	2.19	2.19	2.19	2.19	2.19	2.19	2.19	2.19
7	3.85	3.85	3.85	3.85	3.85	3.85	3.85	3.85
8	6.21	6.21	6.21	6.21	6.21	6.21	6.21	6.21
9	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11
10	2.07	2.07	2.07	2.07	2.07	2.07	2.07	2.07
11	1.93	1.93	1.93	1.93	1.93	1.93	1.93	1.93
12	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56
Annual	29.75	29.75	29.75	29.75	29.75	29.75	29.75	29.75

Table 2
SWAT surface runoff results indicate a non-linear change in runoff on a monthly and annual basis when CN is modified.

Month	+20% Q (mm)	+15% Q (mm)	+10% Q (mm)	+5% Q (mm)	−5% Q (mm)	−10% Q (mm)	−15% Q (mm)	−20% Q (mm)
1	5.1	4.05	3.16	2.41	1.3	0.9	0.6	0.37
2	10.5	8.92	7.5	6.23	4.16	3.33	2.62	2.02
3	1.11	0.64	0.34	0.17	0.03	0.01	0	0
4	7.2	5.13	3.58	2.44	1.03	0.63	0.36	0.19
5	8.26	6.6	5.27	4.2	2.72	2.23	1.83	1.51
6	6.92	5.4	4.12	3.05	1.52	1.01	0.64	0.38
7	11.23	8.92	6.91	5.23	2.75	1.9	1.25	0.78
8	14.39	11.87	9.65	7.77	4.92	3.85	2.96	2.22
9	3.93	2.97	2.18	1.57	0.77	0.52	0.33	0.19
10	6.5	5.06	3.85	2.86	1.44	0.97	0.61	0.36
11	7.94	5.95	4.28	2.95	1.17	0.64	0.31	0.12
12	2.04	1.52	1.12	0.8	0.37	0.24	0.14	0.08
Annual	84.85	66.79	51.76	39.51	22.08	16.13	11.58	8.16

Table 3
SWAT surface runoff (mm) results for April as percent change between predicted surface runoff values indicate the high degree of CN sensitivity.

	5	10	15	20	−5	−10	−15	−20
5	0.00	31.84	52.44	66.11	−136.89	−287.30	−577.78	−1184.21
	10	0.00	30.21	50.28	−247.57	−468.25	−894.44	−1784.21
		15	0.00	28.75	−398.06	−714.29	−1325.00	−2600.00
			20	0.00	−599.03	−1042.86	−1900.00	−3689.47
				−5	0.00	−63.49	−186.11	−442.11
					−10	0.00	−75.00	−231.58
						−15	0.00	−89.47
							−20	0.00

Table 4
Curve numbers generated for the River Njoro watershed using the land cover and land use maps and classification scheme from Baldyga et al. (2007).

Land use	Hydrologic soil group				% Cover
	A	B	C	D	
Grass	49	69	79	84	50
Dense vegetation	30	30	41	48	80
Plantation	32	58	72	79	80
Riparian	30	30	41	48	80
Urban	91	91	91	91	0
Degraded	77	86	91	94	20
Large agriculture	67	78	85	89	50
Small agriculture	68	79	86	89	70
Basalt vegetation	49	69	79	84	50
Acacia	36	60	73	79	50
Euphorbia	49	68	79	84	80
Salt flats	63	77	85	90	0

urban settlements and then terminating at 1759 masl in Lake Nakuru, a shallow soda lake typical of the Rift Valley.

Five streams flow into Lake Nakuru: Njoro, Nderit, Makalia, Lamudiac, and Ngosur. Of the five streams, it is estimated that the River Njoro provides 65% of the total stream inflow (Gichuki et al., 1997). Siltation and fertilizer pollution from agricultural runoff are considered immediate threats to the Lake Nakuru environment, including its river system, as identified by several recent studies in the region (Okoth et al., 2009; Kibichii et al., 2008; Shivoga et al., 2007).

Climate in the Njoro region is characterized by a bimodal precipitation pattern with long rains occurring from April–May and short rains occurring from November–December with, an additional small peak that occurs in August. Mean annual rainfall measured at Njoro town center is 939 mm. Average annual minimum and maximum temperatures for the area range are 9 °C and 24 °C, respectively, with an average annual temperature of

Table 5
River Njoro land cover and land use types with corresponding US land cover types used to assign SWAT CN's.

Land use	Corresponding land use (Rawls et al., 1993; USDA-NRCS, 1986)
Grass	Pasture, grassland or range under continuous forage in **fair** condition with 50–70% cover though not heavily grazed
Dense vegetation	Oak – Aspen in **good** condition
Plantation	Woods – Grass combination in **good** condition
Riparian	Oak – Aspen in **good** condition
Urban	Impervious areas
degraded	Developed urban areas
Large agriculture	Row crops in **good** condition
Small agriculture	Pasture, grassland or range under continuous forage in **poor** condition with 50–70% cover though not heavily grazed
Basalt vegetation	Pasture, grassland or range under continuous forage in **fair** condition with 50–70% cover though not heavily grazed
Acacia	Woods – Grass combination in **fair** condition
Euphorbia	Desert shrub in **good** condition
Salt flats	Natural desert landscape

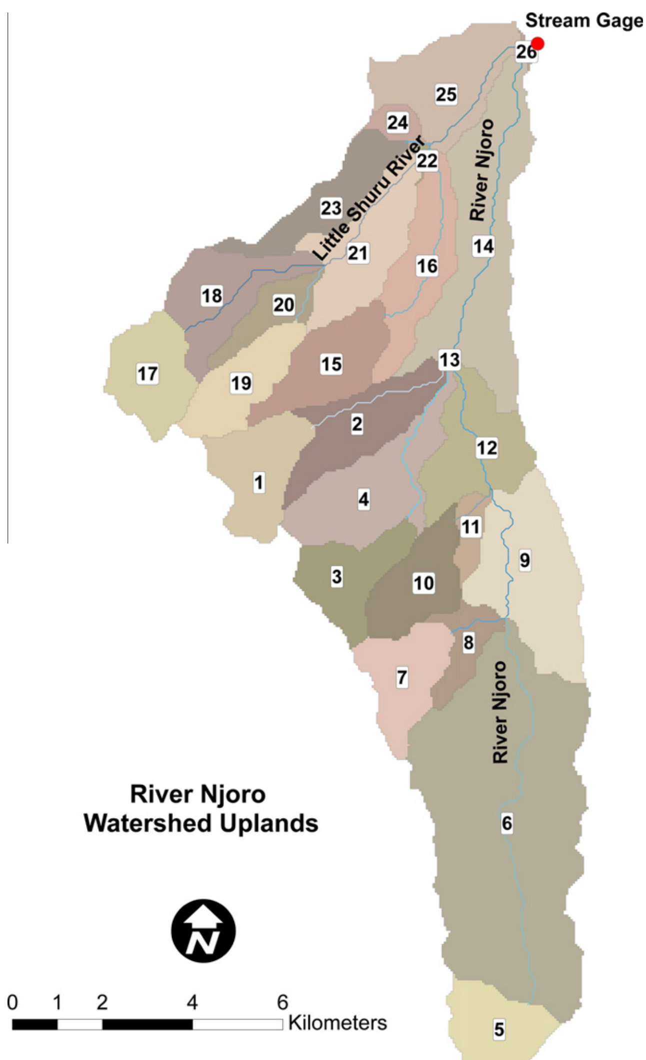

Fig. 2. Discretized watershed with 26 planes and 17 channels. Colors are arbitrary and used only to illustrate subdivided watershed complexity.

17.4 °C (Source: Republic of Kenya Ministry of Water and Irrigation).

Vegetation cover in the watershed ranges from 0% in areas affected by anthropogenic practices such as agriculture and livestock husbandry to 90% in upland indigenous forests. The watershed's uplands can be characterized into three principle vegetation zones (Mathooko and Kariuki, 2000): heavily grazed moorlands are found in the uppermost section and bordering a dense closed canopy indigenous montane forest mixed with bamboo; lower in elevation, tracts of intact and deforested plantations are present consisting of various *Cupressus* and *Pinus* species; and further downslope, tracts of agricultural and pasture lands are dominant. Basic crops grown in the region include legumes, maize, sorghum, pyrethrum, wheat, barley, tomatoes, cabbages, yams, and potatoes. The diverse vegetation found in the watershed serves a wide range of purposes including timber harvesting, medicine, human food, livestock fodder, building material, and fuel wood.

3. Methodology

3.1. Soil and Water Assessment Tool (SWAT)

For this study, the SWAT2000 (Neitsch et al., 2002) model was used via the Automated Geospatial Watershed Assessment (AGWA; Miller et al., 2007) tool to simulate hydrologic response in the River Njoro watershed over a 9-year period beginning in 1990. AGWA is a GIS-driven suite of tools that can be used for distributed hydrologic modeling and visualization as an extension in Environmental Systems Research Institute's ArcView program. Within the AGWA modeling environment, all aspects of SWAT model parameterization and results visualization can be achieved.

SWAT is a physically based semi-distributed hydrologic model operating on a daily time step and uses a modified Soil Conservation Service-Curve Number (SCS CN) method to calculate runoff. Numerous descriptions of the SCS CN method and its use can be found in the literature (Bondelid et al., 1982; Hjelmfelt, 1991; Lenhart et al., 2002; Melesse and Shih, 2002; Rawls et al., 1993; USDA-NRCS, 1986). Using the SCS CN methodology, SWAT allows the user to quantify the relative impact of management, soil, climate, and vegetation changes at the subwatershed level (Arnold and Allen, 1998; Hjelmfelt, 1991).

Because SWAT is also a deterministic model, each successive model run that uses the same inputs will produce the same outputs. This type of model is preferred for isolating hydrologic response to a single variable, such as land cover and land use change (e.g., management decisions), allowing the impact of any change to be isolated and analyzed for its effect on hydrologic response. Ideally, a model should be non-stationary (such as SWAT) or be able to account for parameter variation through time.

3.2. Data preparation

To build model input files for SWAT, AGWA requires a digital elevation model (DEM), land cover and land use information, soils, and basic climate data. SWAT subdivides a watershed into individual hydrologic response units (HRU) and treats the HRU as a homogeneous block of land use, management techniques, and soil

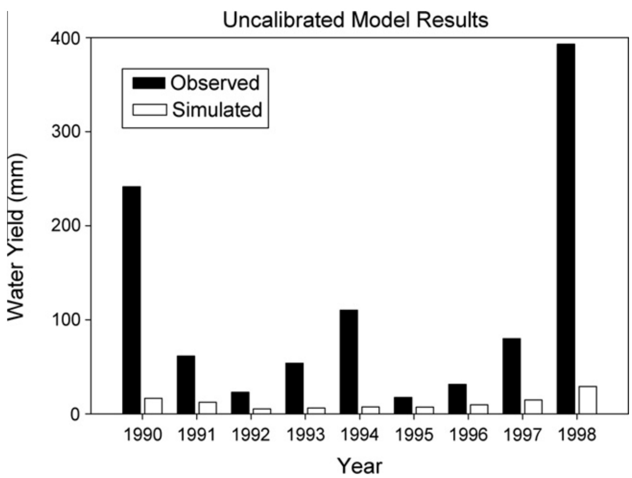

Fig. 3. Initial uncalibrated model results for total annual water yield (mm) using AGWA default parameters against observed data from stream gage FC05.

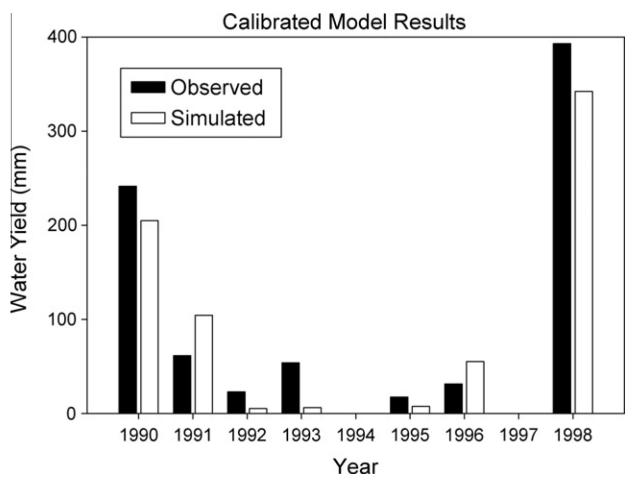

Fig. 4. Post-calibration model results for total annual water yield (mm), excluding years 1997 and 1994. Nash–Sutcliffe model efficiency for these data is 0.93.

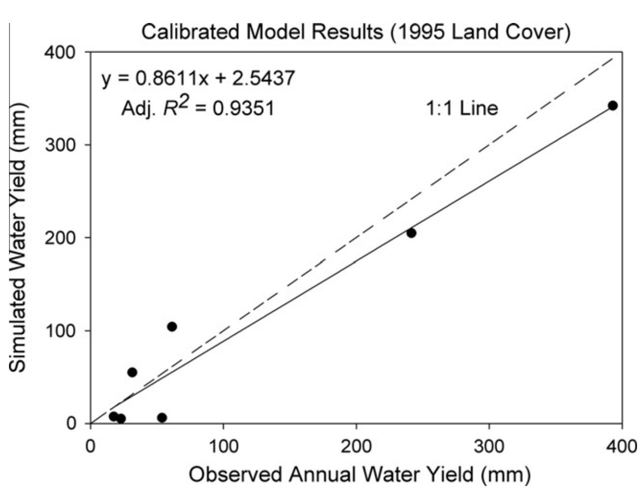

Fig. 5. Coefficient of determination results (R^2), excluding 1994 and 1997, indicate that SWAT is under predicting runoff response to precipitation, particularly for low flow events.

properties and then quantifies the relative impact of vegetation, management, soil, and climate changes within each HRU (Arnold and Allen, 1998; Hjelmfelt, 1991). Using SWAT within the AGWA environment allows a user to also spatially delineate HRUs based on a digital elevation model (DEM). Subdividing the watershed allows users to analyze hydrologic processes in different subwatersheds within a larger watershed and understand localized land use management impacts.

We constructed a 50 m resolution DEM from 1:50,000 contour maps published for the Government of Kenya by the British Government's Ministry of Overseas Development. Land cover and land use maps used were developed by Baldyga et al. (2007). Baldyga et al. (2007) mapped land cover and land use based on Landsat TM and ETM+ satellite imagery from 1986, 1995, and 2000 and identified the greatest amount of land use conversion from indigenous and plantation forest to smallholder agriculture after 1995. They were able to map indigenous forest, plantation forest, rangelands, small-scale agriculture, medium-scale agriculture, large-scale agriculture, urban, and water at each time step.

A soil map generated by Mainuri (2005) for the River Njoro watershed was used as input to AGWA and to determine soil parameters, such as texture, hydrologic soil group (HSG), and available water content for soils as needed to run SWAT.

Precipitation data required by SWAT were available for the Njoro Town Centre climate station located in the central portion of the watershed and were used to build the required input (Source: Republic of Kenya Ministry of Water and Irrigation). These data were evaluated for consistency and completeness of their record, from which we built daily rainfall observations to drive the model. To simulate weather when there were gaps in observation data SWAT uses the WXGEN stochastic weather generator model (Neitsch et al., 2002). The WXGEN model uses monthly statistics calculated from daily weather data to fill-in missing daily climate data or to simulate weather based on these statistics. We built WXGEN input files from the 20-year record at Njoro following Neitsch et al., 2002. We then selected a 9-year period of rainfall for the period of 1990–1999 that corresponded to the period of record for which streamflow data were available for model calibration.

3.2.1. Parameter sensitivity

Quantifying model sensitivity to parameter changes is an important step in understanding model performance, and a crucial undertaking prior to model calibration; therefore, addressing whether the appropriate quantity and quality of data can be obtained to provide realistic model outputs given parameter sensitivity. Initially, four SWAT parameters were chosen to test surface runoff response sensitivity: curve number (CN), percent land cover, saturated hydraulic conductivity (KS), and soil hydrologic value (HV). These parameters were selected because field data, spatially distributed throughout the watershed, were available from Baldyga et al. (2007) and Mainuri (2005) and provided some indication of parameter ranges. Due to the overall dearth of data available, a simple method was chosen whereby each parameter was independently incremented in 5% steps from −20% to +20% and used as model input. This produced an isolated direct surface runoff response to the parameter in question.

Parameters that affect simulated groundwater processes were not tested for sensitivity because groundwater data for the watershed is limited, although there is evidence that the system is groundwater driven (McCall, 1957). Table 1 displays surface runoff results on a monthly as well as an annual basis resulting from changes in percent land cover. Similarly, there were no changes in direct surface runoff when KS or HV values were modified following the same procedure. Tables 2 and 3, however, illustrate results in predicted surface runoff when CN is modified. As represented in Table 3, a change in land cover classification with

Table 6
SWAT groundwater parameters modified and calibration values used.

Parameter	Description	Default	Calibration
SHALLST	Initial shallow aquifer depth	2000 mm	100 mm
ALPHA_BF	Groundwater flow response to recharge. Range is 0–1, with 0 indicating no connection to groundwater	0	0.5
GWQMN	Depth of shallow aquifer required for return flow	2000 mm	50 mm
GW_REVAP	Indication of how restricted flow is from the shallow aquifer into the unsaturated zone. Range is 0–1, with 0 indicating water movement to the root zone is restricted and 1 indicating that water movement to the root zone approaches rate of potential evapotranspiration	0.2	0.05
REVAPMN	Minimum water depth before water can percolate from shallow aquifer into unsaturated zone or deep aquifer	1500 mm	5 mm

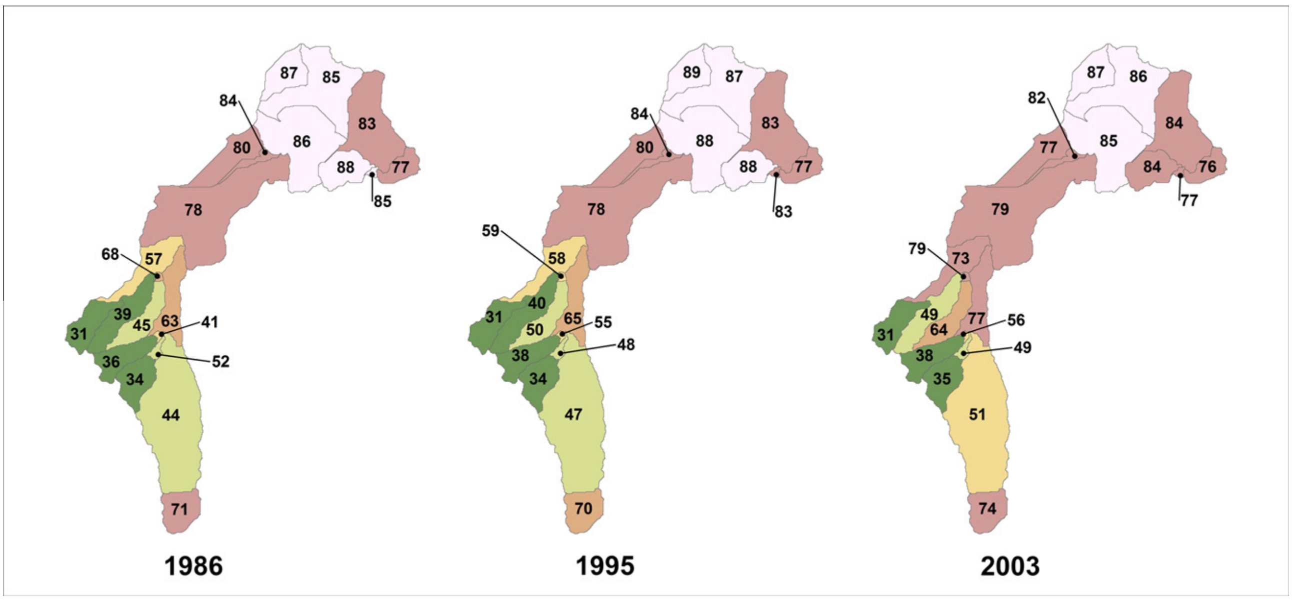

Fig. 6. Curve number changes for each land use map (from Baldyga et al., 2007) show the greatest changes occurring above the stream gauge at the confluence of the Little Shuru and the River Njoro.

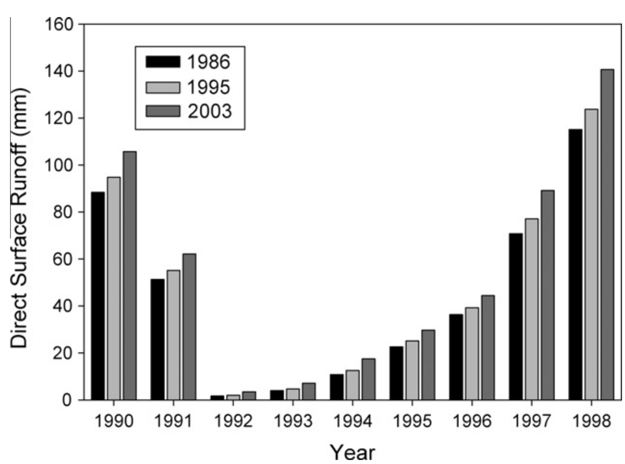

Fig. 7. Direct surface runoff (Q, mm) simulated results for each of three land cover maps using observed rainfall from 1990 to 1998.

concomitant CN modification will result in a notable and nonlinear change in hydrologic response. This analysis also indicates that SWAT is less sensitive to an increase in CN than to a decrease.

3.2.2. Curve number selection

The SCS Curve Number methodology was developed for use in small agricultural watersheds and subsequently applied on a wide range of watershed types. Numbers have been developed and published for a wide range of land cover types and uses (e.g., Rawls et al., 1993). CN's presented by Rawls et al. (1993) and USDA-NRCS TR-55 (1986) were used as initial guidelines for CN development in the River Njoro watershed. CN's derived from tables found in Rawls et al. (1993) and USDA-NRCS TR-55 (1986) and used in this study are listed in Table 4. Table 5 lists land cover types in the River Njoro watershed and comparative land cover types from CN tables.

Modifications were necessary in several instances due to unique characteristics of land cover in the River Njoro watershed. For example, urban land cover in the United States includes a greater degree of impervious human generated materials such as concrete. For this study area, urban areas have fewer impervious surfaces and structures within urban areas may be interspersed with improved pastures. Road surfaces range from dirt to tarmac, with the uplands region dominated exclusively by dirt roads and trails (Obare et al., 2003). As a result, the urban CN, 98, for urban areas in the US was considered too high.

3.3. Model performance

Based on "goodness-of-fit" procedures put forth by Haan et al. (1982) and further analyzed by Martinez-Rodriguez (1999), the Nash–Sutcliffe coefficient (NSE; Nash and Sutcliffe, 1970) was chosen as the most suitable method for judging goodness-of-fit for calibration results with observed data. NSE was calculated using the following equation:

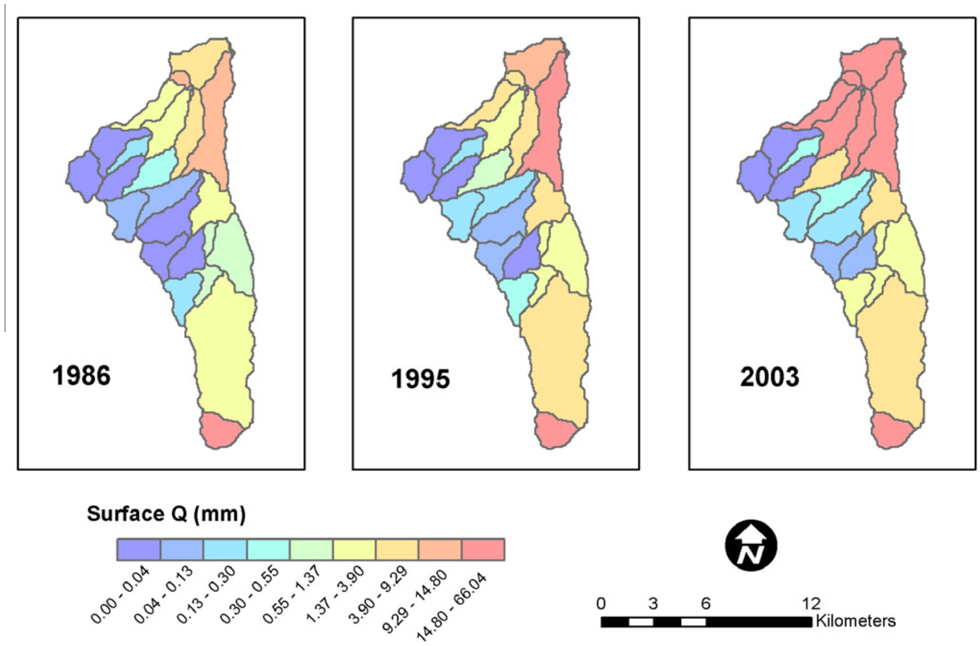

Fig. 8. Simulated direct surface runoff for three land use scenarios developed by Baldyga et al. (2007), using the soils map generated by Mainuri (2005) and observed rainfall from 1990 to 1998 to parameterize SWAT.

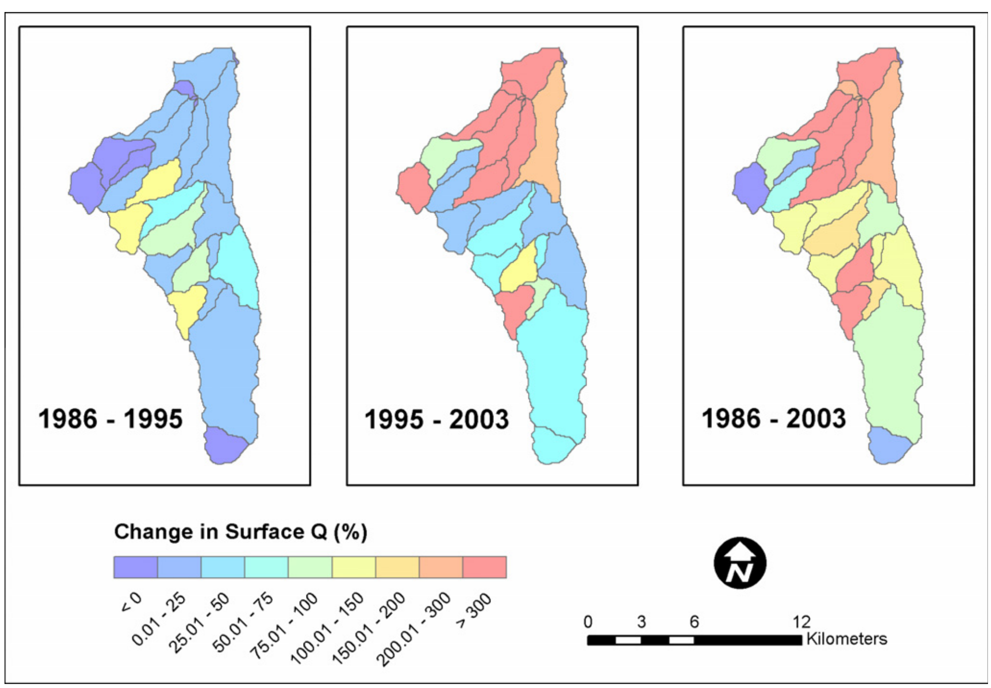

Fig. 9. Percent change in average total annual direct surface runoff (Q, mm) between each of three land use scenarios modeled.

$$NSE = 1\frac{\sum_{i=1}^{n}(Q_{obs} - Q_{sim})^2}{\sum_{i=1}^{n}(Q_{obs} - \bar{Q})^2}$$

Values for NSE can range from 1 to negative ∞ values. If $NSE = 0$, then the model prediction is no better than using average annual runoff volume as a predictor of runoff. Results between zero and one are indicative of the most efficient parameters for model predictive ability, and NSE values of 1 indicate perfect alignment between simulated and observed values.

4. Results and discussion

A benefit to using the SWAT model is that it was originally designed to assess the role topography, soils, land use, and climate play in the hydrologic response of large ungauged basins where data used to develop input parameters may be scarce or absent entirely (Arnold and Allen, 1998; Srinivasan et al., 1998, 2010). SWAT therefore requires hydrography, land management, soils, and basic weather characteristics to estimate the principle input parameters (Neitsch et al., 2002). These may be available in global public do-

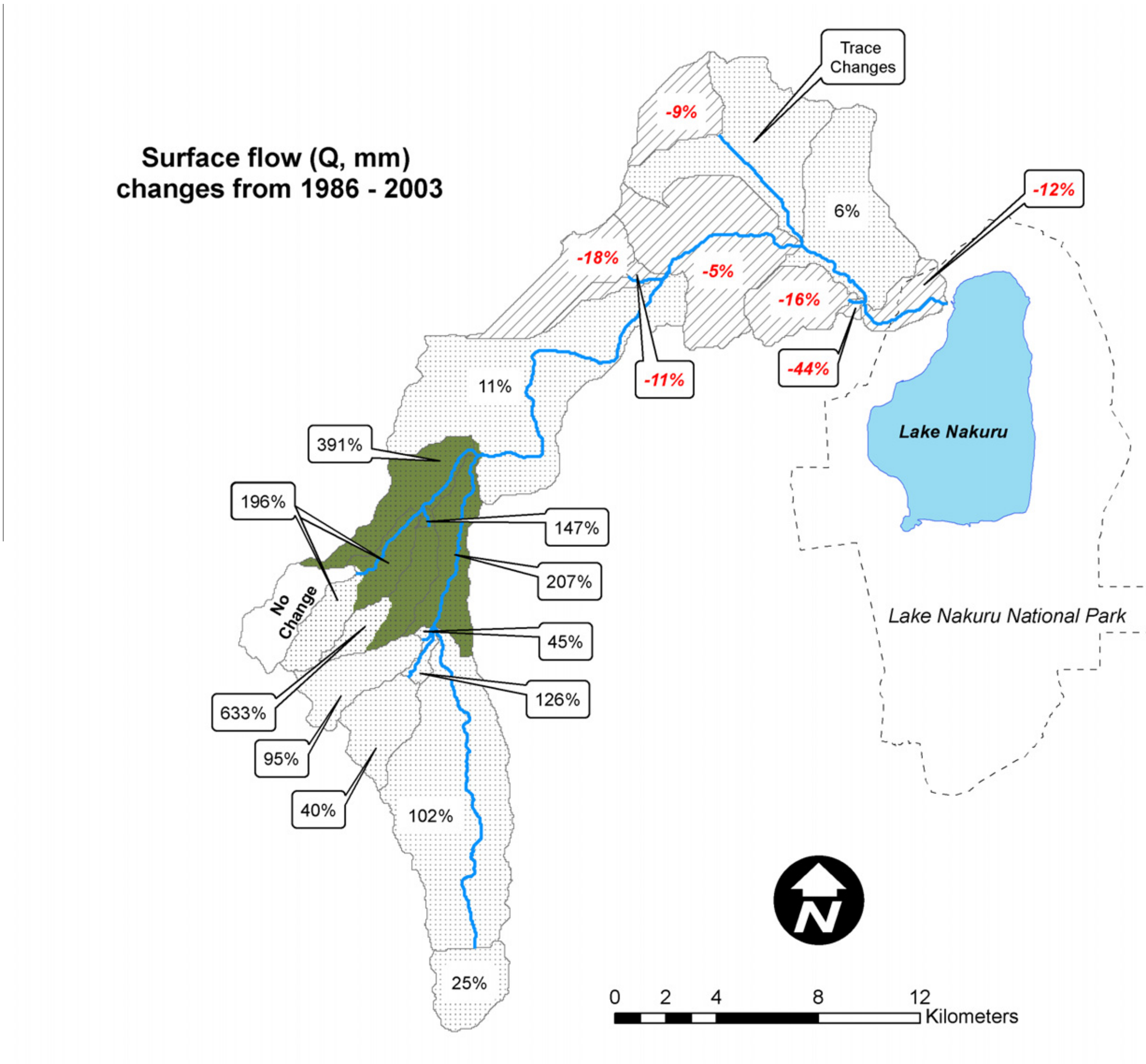

Fig. 10. Changes in surface flow throughout the full length of the River Njoro watershed show dramatic increase surface runoff from the uplands with decreases downstream.

main data sets or derived in a GIS environment from satellite imagery and digital elevation models. In developing nations, this is beneficial because it is not uncommon to have few historical data available or to lack active monitoring in watersheds.

SWAT can be used as a trend model, allowing a user to analyze the relative magnitude and direction of hydrologic change resulting from land management decisions, insofar as the modeling goal is to mimic the rate of change or trend within the system (Arnold and Allen, 1998; Srinivasan et al., 2010; http://www.brc.tamus.edu/swat/). For this study, SWAT was selected because there were some rainfall and runoff data available during the 1990s that corresponded with Landsat imagery and we were able to use field data collected by Mainuri (2005) to improve our understanding of the spatial distribution of soils. Other distributed hydrological models represent varying degrees of complexity, and although governed by well-established laws and relationships, require more data both spatially and temporally to paramterize the models than are often available in regions such as East Africa (Ndomba et al., 2008).

4.1. Model calibration

We manually calibrated the SWAT model on an annual basis to an observation station on the Njoro River just below the confluence of the Little Shuru River with the River Njoro (Gage ID FC05) and using the 1995 land use data developed by Baldyga et al. (2007). The watershed contributing runoff to FC05 is approximately 116 km^2. AGWA was used to discretize the watershed into HRUs and channels using a contributing source area for channel development of 350 ha. This watershed configuration, shown in Fig. 2, resulted in 26 planes and 17 channels, with the outlet being located in plane 26.

Using default parameters in SWAT, as set by AGWA, to simulate annual runoff over 9 years resulted in an under-prediction of annual water yield for each year (Fig. 3), due to the underestimation of groundwater influence on streamflow. Although the extent of groundwater contribution to River Njoro flows is not completely known due to a lack of groundwater wells with historical data, field observations of shallow groundwater between 2003 and 2007 coupled with a pumiceous landscape are consistent with findings published by McCall (1957) that indicate a connection to groundwater within the Lake Nakuru basin. Baseflow separation estimates from FC05 gage showed that between 20% and 50% of annual water yield is from groundwater.

Groundwater parameters in the SWAT groundwater configuration (.gw) files were iteratively modified until the basic shape of the annual water yield output curve from SWAT matched annual

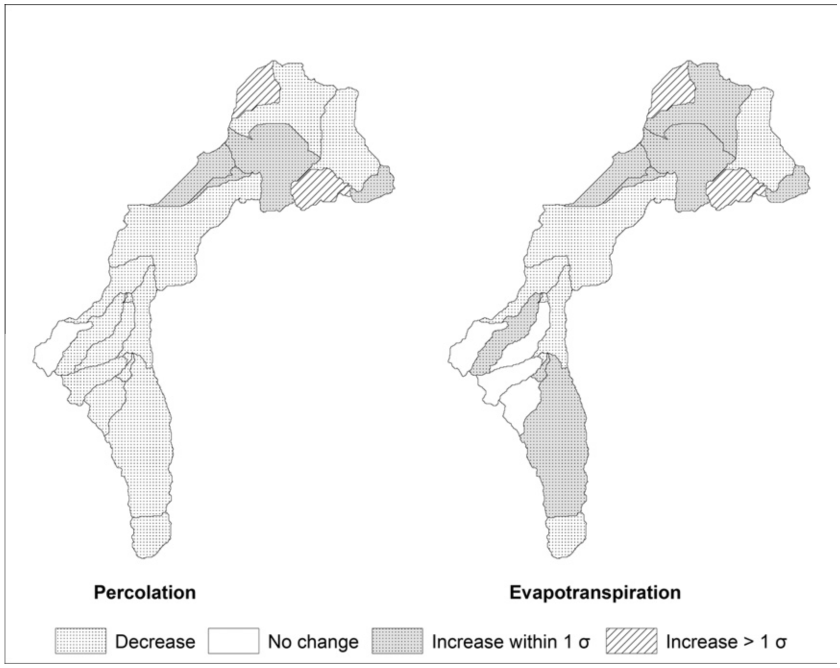

Fig. 11. Changes in how precipitation is partitioned within the River Njoro watershed from 1986 to 2003 indicate that within the uplands once forested region there is an overall decrease in groundwater recharge coincident with several areas of reduced evapotranspiration. Only a few areas in the lower watershed show groundwater recharge.

observed data (Figs. 4 and 5 and Table 6). Ultimately, runoff data from 1994 and 1997 were excluded from the final calibration because there were >100 missing days in the observational record for each of these years, with the majority of those days falling during the rainy season. As an indication of problem severity: 1997 was the highest recorded rainfall during the simulation period (an El Niño year), but it had a lower-than-average recorded runoff volume.

Final Nash–Sutcliffe model efficiency result for the annual calibration plot was 0.93 (Fig. 4) and the regression coefficient of determination (R^2) was 0.95. Model validation was not carried out for this watershed. Few historical data were available and were used for model parameterization and calibration. Results from this modeling exercise are intended to be used only as an indication of the magnitude and direction of change in the rainfall–runoff response to land use changes.

4.2. Simulations

Parameter settings identified during model calibration were used to parameterize the SWAT model with additional land use inputs for the period representing pre-transition (1986) and post-transition (2003). The watershed contributing runoff to FC05 was simulated using the same watershed configuration as the calibration data set. We then extended the modeling environment to include the entire watershed to the outlet at Lake Nakuru with the assumption that model parameters developed for the FC05 watershed would transfer directly to the rest of the watershed. Inputs for the lower portion of the watershed, which has undergone few changes during the calibration period and a more homogeneous landscape, were developed using the same methodology as inputs for the upland region. Coupled with NSE results, there is strong justification for using the identified parameters as input to hydrologic modeling efforts for the entire watershed over a longer period to assess watershed response to land use change (Miller et al., 2002; Srinivasan et al., 2010). Each of the three simulations (1986, 1995, and 2003) used the same climate and soils data so that the effects of land cover change on hydrologic response, as reflected by changes in CN (Fig. 6), were isolated following Miller et al. (2002).

4.2.1. Uplands

SWAT results were interpreted at both the outlet and using a spatially distributed approach based on HRUs. Direct surface runoff to the FC05 watershed outlet was simulated under the three different land cover scenarios (1986, 1995, and 2003), illustrating the cumulative effect of land cover change in terms of total delivery to the outlet (Fig. 7). Increases in direct surface runoff were spatially distributed in the watershed above FC05, with the greatest changes occurring in lower HRUs (near the gage) and relatively low increases in the uppermost portions of the watershed (Fig. 8). AGWA's visualization tools were used to quantify the percent change in surface runoff between years (Fig. 9) per HRU. From 1986 to 1995, surface runoff from subwatersheds show only slight increases ranging from 0% to 25%. These areas were still primarily under plantation forest intermittently during the 9-year period (Baldyga et al., 2007). In contrast, between 1995 and 2003 simulated surface runoff increased in those same subwatersheds in some case by more than 300%. It is within these subwatersheds near the outlet that the greatest changes were reported in land use from forest to small-scale agriculture and managed grass by Baldyga et al. (2007).

4.2.2. Model results for the watershed to Lake Nakuru

Results for runoff simulation to the outlet of the river to Lake Nakuru show a greater variability in change due to land cover (Fig. 10). While most of the watershed shows an increase in runoff, there are portions of the watershed identified as having reduced discharge. The majority of the watershed has undergone an increase in surface runoff (Figs. 8 and 9), which is interpreted as having a flashier flow regime and more rapid conversion of rainfall to runoff into Lake Nakuru. This pattern is consistent with anecdotal evidence gathered from local community meetings where people reported that the timing of river flows had changed appreciably.

Table 7
SWAT output depicting changes in how water is partitioned within the watershed, and consequences for supporting water users.

Category	Water yield	Surface runoff	Groundwater recharge
1995 Vegetation	148 mm	108 mm	127 mm
2003 Vegetation	151 mm	118 mm	118 mm
Change from 1995 to 2003 (mm)	+3	+10	−9
Change from 1995 to 2003 (%)	+2	+9	−7
Change from 1995 to 2003 in people supported by water source[a]	+15,000	+50,000	−44,509

[a] Assuming 150 l per day per person.

These changes are coincident with significant changes in watershed land cover, resulting from overall forest conversion to agriculture within the region and increases in other human activities (Baldyga et al., 2007). At one time, the river was considered a highly productive trout stream, suggesting continuously flowing cold water. However, fish are now absent in all stream reaches. Flow reductions, including flow cessation in lower reaches, during the dry season are negatively impacting agricultural production and, as a consequence, overall water and food security and the ecology of Lake Nakuru are at risk.

There are two principle reasons for the hydrological changes seen in the River Njoro watershed between 1986 and 2003. The decrease in forested areas in the uplands led to a decline in infiltration due to the reduction in surface roughness and litter as well as reductions in average annual evapotranspiration (Fig. 11); however, overall there was no perceptible change in average annual evapotranspiration. Therefore, the overall net result is that a higher proportion of rainfall is being converted into surface runoff, rather than infiltrating into the soil and recharging the regional aquifer.

The net effect of land cover conversion was as expected an overall slight increase in water yield, expressed as the total discharge from the outlet of the river resulting from both surface runoff and river flow supported by water migrating to the river from the soil, which occurs when the soil is relatively well saturated. While the overall effect on water yield was relatively small (an increase from 148 mm/yr to 151 mm/yr), the proportion of water yield resulting from surface runoff increased significantly at the expense of soil water flow. Surface runoff increased by 9% while lateral flow was reduced by approximately 2%. The increase in surface water was offset by a commensurate decline in groundwater recharge (Table 7), which declined by 7%. Again, these changes are due to two reasons: (1) declines in evapotranspiration due to the reduction in forest cover (Baldyga et al., 2007), and (2) a higher proportion of rainfall being converted into surface runoff instead of infiltrating into the soil and migrating to the regional aquifer (Fig. 11).

Previous studies have found the hydrologic models used in Great Lakes Region of East Africa exhibit a high degree of uncertainty because there is a poor understanding of outflow of lakes to rivers (Ayenew and Becht, 2008; Schuol et al., 2007). In Kingston and Taylor's (2010) Nile Basin study using SWAT, the authors found that the model was sensitive to the shallow aquifer threshold level, which supports the challenges others have found in defining the relationship between streamflow and groundwater in this region. Geological surveys carried out in 1957 and 1967 described the region as volcanic and characterized by porous pumiceous formations (McCall, 1957, 1967). These studies further indicated that for Lake Nakuru, which is the terminus for the River Njoro, recharge is not exclusively by way of surface water runoff. Rather, lake recharge is primarily through groundwater accruals from stream losses through the highly porous landscape. This present study paints a compelling picture that recharge within the Lake Nakuru Basin is being critically impacted.

Humans rely on water for a range of household, animal husbandry, and industrial uses, and people within the watershed source their water from both surface and groundwater withdrawal points. There is a trade-off involved in the sourcing of water: groundwater costs more but has higher water quality and lower risk of pathogens and water-borne disease. Changes in the apportionment of water into surface versus groundwater recharge have direct implications for human water use, with our simulations showing the net effect of reducing groundwater reserves and impacting borehole function.

Surface water is generally considered a less preferred water resource than groundwater (Calow and MacDonald, 2009; Braune and Xu, 2009; Calow et al., 1997), particularly in arid and semi-arid regions where interannual precipitation variation is high, which is the case throughout much of sub-Saharan Africa (Shahin, 2002; Calow et al., 1997). Interannual precipitation can be highly variable, and high intensity seasonal rainfall can lead to challenges in water utilization due to the offset in time between water availability and need, resulting in greater demand for water storage to buffer communities against these offsets and variability. Coupled with unreliability, semi-arid and arid regions also face the challenge of protecting surface water from contamination. In areas where communities rely more heavily on surface water resources for domestic activities, such as domestic water collection, laundry washing, and livestock watering, then riparian corridor degradation will also increase. Degradation of riparian areas can further exacerbate water quantity and quality issues due to declines in healthy vegetation buffer systems that deter direct surface water contamination (Shivoga et al., 2007).

There is a clear shift in allocations of surface and groundwater recharge within the River Njoro watershed, with an estimated associated impact on water availability for human use (Table 7). It is challenging to identify the minimum human requirements for domestic water consumption; the WHO identifies a minimum standard of 15 l per person per day, but this is strictly for consumption and sanitation and more reasonable estimates for domestic use that include cooking, cleaning, and other household duties range from 100 to 200 l per person per day as a minimum. In Table 7, the trade-off in changes to the water balance is represented in terms of human consumption with an assumption of 150 l per person daily use. The overall net effect is an increase in water availability due to increases surface runoff and a decline in groundwater availability, but the amount of water actually available to humans via surface runoff is actually much lower due to the high variability in runoff throughout the year; much of the runoff pulses through the watershed in response to high rainfall events and quickly is lost to the lake.

Ecological effects are primarily negative with this kind of shift in water delivery. While Lake Nakuru relies on river flow to periodically increase its volume, especially in high rainfall years, the shift to surface runoff has several outcomes to the lake that are undesirable from an ecological perspective. First, surface runoff is associated with higher erosion and sediment delivery, and the park has identified siltation and sediment transport as issues of serious concern for lake sustainability. While we did not simulate erosion prediction in this effort, increases in surface runoff are linked to increased surface erosion and loss of topsoil and long-term sustainability. Surface runoff, especially in areas with low vegetation cover, results in concentrated flow and increased sediment transport, resulting in higher sediment delivery rates downstream and reduced water quality. Second, surface runoff is more rapid than flow supported by groundwater and/or soil moisture release and downstream runoff will tend to be much flashier. A shift to a flashier system impacts the temporal distribution of flow by increasing runoff during the rainy season but reducing it during the dry season, when ecosystems are particularly stressed. Thus, the net effect can be an increase or negligible change in total runoff on an annual basis while the system is put under stress due to a shift in the timing of the delivery of water.

5. Conclusions

Andersson et al. (2009) successfully used SWAT to simulate daily discharge at 10 gaging stations within the predominately agricultural Thukela watershed in South Africa. Subsequently, they used SWAT (Andersson et al., 2011) to assess potential impacts of in situ water harvesting on smallholder maize yields and river response. In Tanzania, Ndomba et al. (2008) carried out a study in the Pangani River Basin to validate SWAT for use in data scarce regions, such as East Africa. Their study yielded Nash–Sutcliffe model efficiency greater than 0.50 during both calibration and validation; however, they caution that additional research on model validation must be carried out with SWAT before it is widely adopted. Setegn et al. (2010), working in Ethiopia's Lake Tana Basin also report greater than 0.50 Nash–Sutcliffe model efficiency, acknowledging that SWAT has the potential for use in assessing the relative impact of land use management decision on hydrologic response.

In Kenya, SWAT was used to assess the potential impact of climate change on streamflow within the Lake Victoria basin (Githui et al., 2009a). Data available for model calibration covered only 5 years, however, leading the authors to use aggregated monthly data rather than daily data. Kingston and Taylor (2010) similarly found that when using SWAT in the Nile Basin aggregation of daily data to monthly was necessary to achieve an acceptable model calibration. Also in Kenya, several studies have modeled the impact of land cover and land use change on hydrologic response. Githui et al. (2009b) used SWAT in the Nzoia watershed to examine the impacts on base flow and streamflow under current land use change trends (e.g., forest conversion to smallholder agriculture) versus afforestation. They found that flood risks were exacerbated if current land use change trends were to continue. Most recently, Mango et al. (2011) have used SWAT coupled with satellite-based estimated rainfall to support water resources management efforts in the Mara River Basin, demonstrating that it data scarce regions such as East Africa it is possible to approach water resources challenges using scientifically rigorous approaches.

We were able to identify the spatial and temporal aspects of the magnitude and direction of land use change in the River Njoro watershed with the AGWA–SWAT model. Along the river, there was a marked shift to increased surface runoff in the uplands coupled with decreased groundwater recharge. We investigated the rainfall records and could not attribute this result being due to a shift in rainfall totals or timing. Field observations showed that reaches along the river are drying up sooner and for longer periods than in the time prior to the widespread land cover change. This is indicative of a change in hydrograph timing and steepness of the falling limb, which is identified in our modeling effort.

Small watersheds, such as the River Njoro, are more sensitive to short duration high intensity rainfall events because overland flow processes drive response (Haan et al., 1982; Hernandez et al., 1998). Consequently, increased localized flooding from small storm events will result from decreased interception by forest cover, which may impact local food security because crops are primarily rain-fed requiring planting to occur before the onset of the rainy season.

Consequences of rapid changes in the upland areas (Mau Forest) of the River Njoro watershed are being felt by downstream users. Increased streamflow and flashier flows are associated with higher erosion and sediment delivery. Kenya Wildlife Service has identified sediment transport as an issue in Lake Nakuru National Park. Baldyga et al. (2007) reported the presence of algae blooms appearing in Lake Nakuru in more recent years as well, which is considered to be a result of higher nutrient inputs from agricultural runoff from the middle and uplands portions of the River Njoro watershed. Surface runoff is more rapid than flow supported by groundwater or soil moisture release, which leads to flashier flows. A consequence of this flashier flow regime is a decrease in groundwater recharge.

Groundwater recharge reductions can have deleterious effects for people living within the watershed as well as wildlife at Lake Nakuru National Park. As reported by McCall (1957, 1967), Lake Nakuru is primarily recharged through groundwater flow from the surrounding five watersheds. Decreased groundwater recharge will therefore impact Lake Nakuru by lowering water available for recharge, resulting in potential negative impacts on wildlife populations in the park that are dependent on the lake and the environment it supports.

Within the lower portion of the watershed, communities rely heavily on community boreholes and urban wells for their water sourcing. Communities within the upper watershed rely less on boreholes and more on surface water because there is a cost barrier. Flashier flows, however, decrease the seasonal surface water availability as well as increase the risk of pathogens and waterborne disease for those consuming surface water. Coupled with these serious impacts on water resources, is a rapidly increasing human population within the watershed (Baker et al., 2010), particularly in the middle and upper regions. There is a potential for increased conflict over dwindling water resources, particularly between agricultural and pastoral communities within the watershed.

Additional land cover analysis is required during the available period of rainfall–runoff record to establish a statistically valid link between rapid changes (annual) in land cover and observed hydrologic response that would also allow for monthly model calibration to determine if there are additional land management practices contributing to changes in runoff response that need to be addressed. In its current state, this modeling effort is most useful for identifying sensitive areas within the watershed, linking land cover and hydrology, and as a platform for scenario building and decision support.

Funding

This research and publication was made possible as a component of the Global Livestock Collaborative Research Support program supported by USAID Grant No. PCE-G-00-98-00036-00, as well as through contributions from participating institutions. Opinions expressed herein are those of the authors and do not necessarily reflect the views of the United States Agency for International Development.

Acknowledgements

The authors would also like to thank Dr. Ralph Boerner and Dr. Patrick Baker for their review and thoughtful comments on the manuscript during its final preparation.

References

Akotsi, E.F.N., Gachanja, M., Ndirangu, J.K., 2006. Changes in Forest Cover in Kenya's Five "Water Towers" 2000–2003. Report of the Kenya Forests Working Group.

Andersson, J.C.M., Zehnder, A.J.B., Jewitt, G.P.W., Yang, H., 2009. Water availability, demand and reliability of in situ water harvesting in smallholder rain-fed agriculture in the Thukela River Basin. Hydrol. Earth Syst. Sci. 13, 2329–2347.

Andersson, J.C.M., Zehnder, A.J.B., Rockström, J., Yang, H., 2011. Potential impacts of water harvesting and ecological sanitation on crop yield, evaporation and river flow regimes in the Thukela River Basin, South Africa. Agric. Water Manage. 98, 1113–1124.

Arnold, J.G., Allen, P.M., 1998. Estimating hydrologic budgets for three Illinois watersheds. J. Hydrol. 176, 57–77.

Ayenew, T., Becht, R., 2008. Comparative assessment of the water balance and hydrology of selected Ethiopian and Kenyan Rift Lakes. Lakes Reserv. Res. Manage. 13, 181–196.

Baker, T.J., Miller, S.N., Prager, S.D., Legg, D., 2010. Disaggregating human population for improved land use management decision making. Land Use Sci. 5 (4), 237–257.

Baldyga, T.J., Miller, S.N., Driese, K.L., Gichaba, C.M., 2007. Land cover change assessment within Kenya's Mau Forest region Using Remotely Sensed Data. Afr. J. Ecol. 46, 46–54.

Bondelid, T.R., McCuen, R.H., Jackson, T.J., 1982. Sensitivity of SCS models to curve number variation. Water Resour. Bull. 18 (1), 111–116.

Bonnell, M., Purandara, B.K., Venkatesh, B., Krishnaswamy, J., Acharya, H.A.K., Sungh, U.V., Jayakumar, R., Chappell, N., 2010. The impact of forest use and reforestation on soil hydraulic conductivity in Western Ghats of India: implications for surface and sub-surface hydrology. J. Hydrol. 391, 47–62.

Braune, E., Xu, Y., 2009. The role of ground water in sub-Saharan Africa. Ground Water 48 (2), 229–238.

Brüijnzeel, L.A., 2004. Hydrological functions of tropical forests: not seeing the soil for the trees? Agric. Ecosyst. Environ. 104 (1), 185–228.

Calder, I.R., 1993. Hydrologic effects of land-use change. In: Maidment, D.R. (Ed.), Handbook of Hydrology. McGraw-Hill, New York, pp. 13.1–13.50.

Calow, R.C., Robins, N.S., MacDonald, A.M., MacDonald, D.M.J., Gibbs, B.R., Orpen, W.R.G., Mtembezeka, P., Andrews, A.J., Appiah, S.O., 1997. Groundwater management in drought-prone areas of Africa. Water Resour. Dev. 13 (2), 241–261.

Calow, R.C., MacDonald, A.M., 2009. What will Climate Change Mean for Groundwater Supply in Africa? ODI Background Note. Overseas Development Institute, London.

Chandler, D.G., 2006. Reversibility of forest conversion impacts on water budgets in tropical karst terrain. For. Ecol. Manage. 224, 95–103.

Comprehensive Assessment of Water Management in Agriculture (CA), 2007. Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture. International Water Management Institute, London: Earthscan, and Colombo.

Gichuki, N., Waanene, K., Gatere, G., 1997. Biodiversity Profile of Nakuru District and Its Environs. Published by the Ministry of Environment and Natural Resources, Kenya.

Githui, F., Gitau, W., Mutua, F., Bauwens, W., 2009a. Climate change impact on SWAT simulated streamflow in western Kenya. Int. J. Climatol. 29, 1823–1834.

Githui, F., Mutua, F., Bauwens, W., 2009b. Estimating the impacts of land-cover change on runoff using the soil and water assessment tool (SWAT): case study of Nzoia catchment, Kenya. Hydrol. Sci. J. 54 (5), 899–908.

Haan, C.T., Johnson, H.P., Brakensiek, D.L. (Eds.), 1982. Hydrologic Modeling of Small Watersheds. American Society of Agricultural Engineers, Michigan.

Hanjra, M.A., Gichuki, F., 2008. Investments in agricultural water management for poverty reduction in Africa: case studies of Limpopo, Nile, and Volta Basins. Nat. Resour. Forum 32, 185–202.

Hernandez, M., Goodrich, D.C., Miller, S.N., Unkirch, C.L., 1998. Landscape Indicator Interface with Hydrologic and Ecological Models. Open File Report USDA-ARS Southwest Watershed Research Center, Tucson, AZ.

Hjelmfelt, A.T., 1991. Investigation of curve number procedure. J. Hydrol. Eng. 17 (6), 725–735.

Kibichii, S., Shivoga, W.A., Muchiri, M., Enanga, E., Miller, S.N., 2008. Seasonality in water quality and its influence on the abundance and distribution of phytoplankton and chironomid larvae in Lake Nakuru. In: Proceedings of the 30th SIL Congress, Montreal, Canada, vol. 30, No. (3), pp. 333–338.

Kingston, D.G., Taylor, R.G., 2010. Sources of uncertainty in climate change impacts on river discharge and groundwater in a headwater catchment of the Upper Nile Basin, Uganda. Hydrol. Earth Syst. Sci. 14, 1297–1308.

Krhoda, G.O., 1988. The impact of resource utilization on the hydrology of the Mau Hills forest in Kenya. Mt. Res. Dev. 8 (2–3), 193–200.

Lelo, F.K., Chiuri, W., Jenkins, M.W., 2005. Managing the River Njoro watershed, Kenya: conflicting laws, policies, and community priorities. In: Proceedings of the International Workshop on African Water Laws: Plural Legislative Frameworks for Rural Water Management in Africa, 26–28 January 2005, Johannesburg, South Africa.

Lenhart, T., Eckhardt, K., Fohrer, N., Frede, H.-G., 2002. Comparison of two different approaches of sensitivity analysis. Phys. Chem. Earth 27, 645–654.

Locatelli, B., Vignola, R., 2009. Managing watershed services of tropical forests and plantations: can meta-analysis help? For. Ecol. Manage. 258, 1864–1870.

McCall, G.J., 1957. Geology and Groundwater Conditions in the Nakuru Area. Technical Report No. 3, Ministry of Works (Hydraulic Branch), Kenya.

McCall, G.J., 1967. Geology of the Nakuru Thomson's Falls – Lake Hannington Area. Published by the Ministry of Natural Resources, Geological Survey of Kenya.

Mainuri, Z.G., 2005. Land Use Effects on the Spatial Distribution of Soil Aggregate Stability within the River Njoro Watershed, Kenya. MS Thesis Submitted to Department of Geography, Egerton University, Kenya.

Mango, L.M., Melesse, A.M., McClain, M.E., Gann, D., Setegn, S.G., 2011. Land use and climate change impacts on the hydrology of the upper Mara River Basin, Kenya: results of a modeling study to support better resource management. Hydrol. Earth Syst. Sci. 15, 2245–2258.

Martinez-Rodriguez, J.G., 1999. Sensitivity Analysis Across Scales and Watershed Discretization Schemes Using ARDBSN Hydrological Model and GIS. PhD Dissertation Submitted to the School of Renewable Natural Resources, The University of Arizona.

Mathooko, J.M., Kariuki, S.T., 2000. Disturbances and species distribution of the riparian vegetation of a Rift Valley stream. Afr. J. Ecol. 38, 123–129.

Melesse, A.M., Shih, S.F., 2002. Spatially distributed storm runoff depth estimation using Landsat images and GIS. Comput. Electron. Agric. 37, 173–183.

Miller, S.N., Kepner, W.G., Mehaffey, M.H., Hernandez, M., Miller, R.C., Goodrich, D.C., Devonhold, K.K., Heggem, D.T., Miller, W.P., 2002. Integrating landscape assessment and hydrologic modeling for land cover change analysis. J. Am. Water Resour. Assoc. 38 (4), 915–929.

Miller, S.N., Semmens, D.J., Goodrich, D.C., Hernandez, M., Miller, R.C., Kepner, W.G., Guertin, D.P., 2007. The automated geospatial assessment tool. Environ. Modell. Softw. 22, 365–367.

Mogaka, H., Gichere, S., Davis, R., Hirji, R., 2005. Climate Variability and Water Resources Degradation in Kenya: Improving Water Resources Development and Management, World Bank Working Paper No. 69, Washington DC.

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models. Part I – A discussion of principles. J. Hydrol. 10 (3), 282–290.

Ndomba, P., Mtalo, F., Killingveit, A., 2008. SWAT model application in a data scarce tropical complex catchment in Tanzania. Phys. Chem. Earth 33, 626–632.

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., King, K.W., 2002. Soil and Water Assessment Tool Theoretical Documentation. USDA-ARS Publication GSWRL 02-01 BRC 02-05 TR-01.

Obare, G.A., Omamo, S.W., Williams, J.C., 2003. Smallholder production structure and rural roads in Africa: the case of Nakuru District, Kenya. Agric. Econ. 1699, 1–10.

Okoth, O.E., Muchiri, M., Shivoga, W.A., Miller, S.N., Rasowo, J., Ngugi, C.C., 2009. Spatial and seasonal variations in phytoplankton community structure in alkaline–saline Lake Nakuru, Kenya. Lakes Reserv. Res. Manage. 14, 57–69.

Rawls, W.J., Ahuja, L.R., Brakensiek, D.L., Shirmohammadi, A., 1993. Infiltration and soil water movement. In: Maidment, D.R. (Ed.), Handbook of Hydrology. McGraw-Hill, New York, pp. 5.1–5.51.

Schuol, J., Abbaspour, K., Yang, H., Srinivasan, R., Zehnder, A.J.B., 2007. Modeling blue and green water availability in Africa. Water Resour. Res. 44, W0406. http://dx.doi.org/10.1029/2007Wr006609.

Setegn, S.G., Dargahi, B., Srinivasan, R., Melesse, A.M., 2010. Modeling of sediment yield from Anjeni-Gaugged watershed, Ethiopia using SWAT model. J. Am. Water Resour. Assoc. 46 (3), 514–526.

Shahin, M., 2002. Hydrology and Water Resources of Africa. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Shivoga, W.A., Muchiri, M., Kibichii, S., Odanga, J., Miller, S.N., Baldyga, T.J., Enanga, E.M., Gichaba, C.M., 2007. Influences of land use/cover on water quality in the upper and middle reaches of River Njoro, Kenya. Lakes Reserv. Res. Manage. 12, 97–105.

Smakhtin, V.U., 2001. Low flow hydrology: a review. J. Hydrol. 240, 147–186.

Srinivasan, R., Arnold, J.G., Jones, C.A., 1998. Hydrologic modeling of the United States with the soil and Water Assessment Tool. Water Res. Dev. 14 (3), 315–325.

Srinivasan, R., Zhang, X., Arnold, J.G., 2010. SWAT ungauged: hydrological budget and crop yield predictions in the Upper Mississippi River basin. Trans. Am. Soc. Biol. Eng. 53 (5), 1533–1546.

USDA-NRCS, 1986. Urban Hydrology for Small Watersheds. USDANRCS Technical Release 55.

Zimmermann, B., Elsenbeer, H., De Moraes, J.M., 2006. The influence of land-use changes on soil hydraulic properties: implications for runoff generation. For. Ecol. Manage. 222 (1–3), 29–38.