Using a modelling approach to predict sedimentation and nutrient loading in poorly gauged tropical watersheds.

Wambugu M.[1, 2,*], Nyandega I.[2] And Kıthıa S.[2]

[1] Department of Environmental Sciences, Karatina University, P. O. Box 1957-10101 Karatina, Kenya

[2] Department of Geography & Environmental Studies, University of Nairobi, P.O. Box 30197-00100 Nairobi, Kenya

*corresponding author:

e-mail: mwajeffa@yahoo.com

Abstract: Many tropical watershed in Africa are undergoing rapid degradation due to human population expansion and unplanned development. The lack of robust systems for stream water quantity and quality monitoring often makes it difficult to predict the health of such watersheds. The Ruiru (439km^2) and Ndarugu (307km^2) watersheds form part of the upper catchments of the Athi River, the second most important river in Kenya. This study utilized the Soil and Water Assessment Tool (SWAT) to simulate sedimentation and sources of phosphorus and nitrates throughout the basins. Results of this study indicate that, under existing land use and management conditions, an average annual sediment load of approximately 305932 tons and 17805 tons enter the Ruiru and Ndarugu rivers and their tributaries respectively. Agricultural dominated sub basins account for 34.9% in Ruiru and 8.8% in Ndarugu respectively compared to forest-dominated sub-basins 8.6 % and 60.3%, urban dominated sub basins 56.4% and 30.8% respectively. Organic phosphate and Organic nitrate loadings were significantly higher than recommended standards for surface water quality ($F=7.98$, $P<0.05$; $F=24.71$, $P<0.05$ respectively). Modeling results are indicative of degrading catchments, a scenario more severe in Ndarugu where sedimentation levels in forest dominated sub basins are higher than agricultural and urban dominated sub basins. A robust watershed monitoring system should be implemented as the first step in developing an Intergrated Water Resources Management (IWRM).

Keywords: SWAT, Water quality, Sediment, nutrient loading, IWRM

1. Introduction

Rivers are susceptible to land use change and continous exploitation (Withers and Jarvie, 2008; Vörösmarty *et al*, 2010). Deterioration of rivers in terms of water quality as a result of unsustainable human activities has become a major environmental concern (Chen and Lu, 2014), which are directly reflected in land use and land cover characteristics (Kang, *et al*., 2010). To make meaningful decisions for effective water quality management, there is need to understand the relationship between land use and water quality as this relationship can be used to target critical land use areas and to institute appropriate measures to minimize pollutant loading in water resources (Abler *et al*., 2002). Population expansion in Kenya is closely associated with a massive increase in demand for land, which is highly related to urban growth and increased agricultural activities. Kenya is classified as one of the water-scarce countries in the world, and land use implications on water systems have been shown to cause far-reaching consequences, both ecologically and economically. The demand for land in the region is largely fueled by agriculture and settlement. The high population expansion and intense land utilization in the catchment are attributed to increased land degradation, leading to degradation of water resources, one of the critical ecosystem services. This ultimately leads to compromised water quality in rivers. Additionally, increased demand for food leads to intensive farming practice and increased destruction of forest cover to open up areas for cultivation.

Modelling approaches have gained interest in water-scarce watersheds, and continue to draw attention especially in poorly gauged basins in most parts of Africa. Several studies have shown that watershed models can accurately predict hydrological processes in poorly gauged and unmonitored watersheds (Onema *et al*., 2012). Reliable and accurate estimates of hydrologic components are not only important for water resources planning and management but are also increasingly relevant to environmental studies (Schroder, 2006). Stream gauges for the Ruiru and Ndarugu watersheds in Central Kenya were established in 2012, but data is collected on a monthly basis although not consistently. To compliment this information, a modelling approach is used to predict water quality parameters in these basins.

2. Study Area

The Ruiru River (1° 4'43.90"S, 36°50'54.24"E) and Ndarugu River (1° 0'49.80"S, 36°55'8.86"E) are major tributaries of Athi-Galana River, the second longest river in Kenya. Both rivers are located in Kiambu County in the central part of Kenya. The rivers originate from Gatamaiyo Forest, the southern-most tip of the Aberdare Ranges (Figure 1). The drainage area of the Ruiru and Ndarugu Rivers are, approximately, 367km2 and 230km2; length of main river channels 40kms and 48km; and average gradients of about 0.057 and 0.054 respectively. Rainfall is predominantly influenced by altitude, with the mean annual rainfall ranging from 500mm in the lower parts and increasing gradually to 200mm in the upper region. The rainfall regime is bimodal, where long rains fall in April and May. This is followed by a cool dry season in July and August, before short rains which fall from October to December. The mean maximum temperatures range from 26^{o}C to 28^{o}C in the eastern and southern parts, and 18^{o}C to 20^{o}C in the Northwest; while the mean minimum temperatures vary between 14^{o}C and 16^{o}C in the eastern parts and ^{o}C to 8^{o}C in the north western parts. The study area is mainly composed of volcanic rocks of varying ages (Saggerson, 1967). To the northeast, geology varies from Miocene to Pleistocene volcanics while intermediate and basic lavas are found to the south. Land use in consists of smallholder mixed farming, large holder farming (mainly tea and coffee), grazing, nature conservation and built up areas. The main economic activity is agriculture in tea, coffee, dairy, poultry, and horticulture farming.

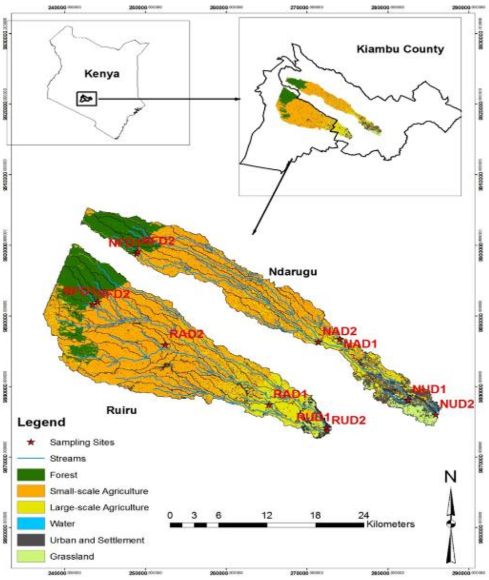

Figure 1: Map of the study area

3. Materials and Methods

The Soil and Water Assessment Tool (SWAT) is a model that is semi-distributed and can be applied at the river basin scale to project the impacts of land management practices on water, sediment and agrochemical yields in watersheds with varying soils, land use and other land use conditions over extended time periods (Arnold *et al.*, 1998). The model is based on the hydrologic cycle, which is centered on the water balance equation:

$$\mathrm{SW}_t = \mathrm{SW}_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - W_{deep} - Q_{day})$$

Where SW_t is the final soil water content (mm H_2O), SW_0 is the initial soil water content on day *i* (mm H_2O), *t* is the time (days), R_{day} is the amount of precipitation on day *i* (mm H_2O), Q_{surf} is the amount of surface runoff on day *i* (mm H_2O), E_a is the amount of evapotranspiration on day *i* (mm H_2O), W_{deep} is the amount of water into the deep aquifer on day *i* (mm H_2O), and Q_w is the amount of return flow on day *i* (mm H_2O). SWAT is designed to utilize the use of alternative data such land use change, land management practices and climate to model such watersheds (Neitsch *et al*., 2005; Arnold *et al*., 1998). The model operates in geographical information system (GIS), making it convenient for definition of watershed features, storage, organization and manipulation of the related spatial and tabular data (Di Luzio *et al*., 2002). The model also runs with minimum data inputs, and this is advantageous in areas where data is scanty or scattered. SWAT has a strong computational efficiency and can model large basins with relatively small computational resources and time. The model application runs in six main steps, namely (1) model installation and data preparation, (2) sub-basin delineation, (3) Hydrological Response Unit (HRU) definition, (4) parameter sensitivity analysis, (5) Model calibration and validation, and (6) uncertainty analysis.

The SWAT requires the use of spatially explicit datasets for land topography, land use and/ or land cover, soil characteristics, and climate and hydrological data on a daily time step. The data types and sources are shown in Table 1. The model was set up and run in QGIS. Because of scarcity of data to calibrate the model, residual analysis, auto and cross-correlations were used to identify key processes for the calibration of the model.

Table 1. Data Sources for SWAT Model

Data Type	Source
Digital Elevation Modem (DEM)	Shuttle Radar Topography Mission (SRTM)
Land use/land cover map	United Nations University - Institute for Water Environment and Health (UNU-INWEH): WaterBase
Soil map	Food and Agriculture Organization (FAO) Soil database Version 3.6
Climate	Climate Forecast System Reanalysis (CFSR): http://globalweather.tamu.edu/
Measured Streamflow	Water Resources Management Authority, Kiambu Regional Office.

Simulated model outputs for water quality parameters were statistically compared with recommended surface water quality standards for Kenya as set out by National Environment Management Authority (NEMA).

4. Results and Discussion

Available long term monitoring data in the two monitoring stations spans a total four years, and is often incomplete due to faulty or non-functional equipment. The use of simulations to provide planners with critical data is therefore a reasonable approach. Like with most simulations, even when they are realistic, they can be used for planning for resources and performing of experiments, but cannot be considered as final. The need for Water Resources Management Authority (WRMA) to upscale their efforts to have more sustained water quality data cannot be over-emphasized.

In this study, one of the most profound effects of watershed processes is observed as increased precipitation between 2011 and 2014. Observed climatic changes are expected to have significant implications on the hydrologic processes, and climate variability is an important factor to be considered for controlling basin hydrologic processes (Qi *et al*., 2009). This has led to higher than normal rainfall and is an impact factor to all other hydrological processes. The upper reaches of both watersheds are under montane forest, and are considered important as far as rainfall distribution is concerned compared to the mid- and lower-reaches. Rainfall in this area is observed to follow an agricultural gradient as described by the agro-ecological zonation.

The pattern of land use and land cover on selected water quality parameters is consistent with expectations in the Ruiru watershed but highly dynamic in Ndarugu watershed (Figure 2). Land use patterns have been shown to lead to impacts on stream flow processes (Grey *et al*., 2014). Typically, an increased urban landscape would lead to an increase in stream flow. In this study, there is a shift towards urban land use but it is not considered significant to have an influence in stream flow. Continuous spread of the urban landscape is expected to lead to a higher flow in subsequent years, although climate-change induced flooding is seen as a more immediate cause for concern to planners in the region.

An increase in forest cover is desirable as this may reduce the impacts of flooding that may be occasioned by increased precipitation. In Ndarugu watershed however, forest dominated sub-basins record the highest sedimentation levels. Between 2011 and 2014, several flooding events have been reported in the region, including urban areas adjacent to the region such as Nairobi. Poor state of planning of infrastructural facilities has often led to disastrous environmental impacts. When this is coupled with an increasing population and urbanization of urban fringe, the potential impacts of flooding to property and life is significant.

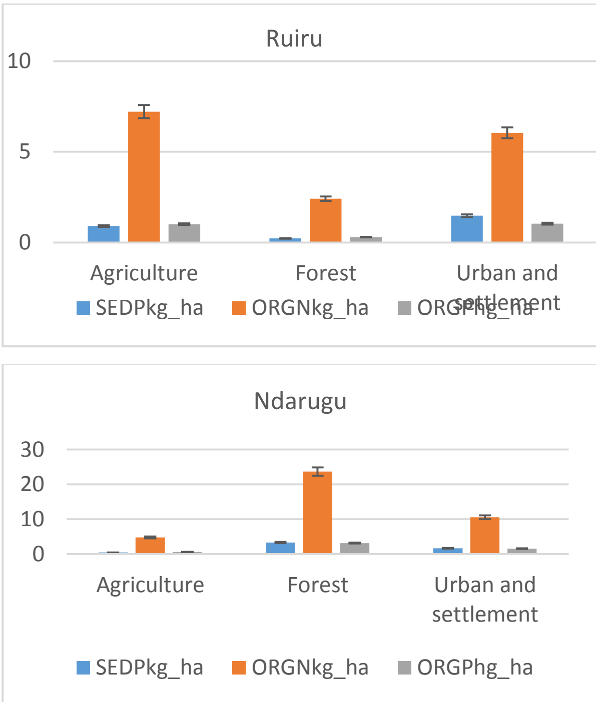

Figure 2: Levels of organic phosphates, nitrates and sediment loading in agriculture-dominated, forest-dominated and urban/settlement dominated sub basins.

Because agriculture in the region is largely rain-fed, increasing amounts of rainfall means that there is higher availability of surface water and soil moisture that is available for agricultural practices. In this regards, the model is considered useful on interactions between precipitation and socio-economic activities, especially agriculture. Specifically, the model generates a range of hydrological parameters that can be incorporated by resource managers to arrive at rational water-related decisions. For example, incorporating nutrient loads generated from land use activities, which are then

Table 2. Simulated vs recommended water quality parameters on Ruiru and Ndarugu Watersheds, Kiambu County

Parameter	NEMA standard	N	Ruiru	Ndarugu		p value
			Mean± SD	Mean± SD	F	
SEDPkg_ha	30 (mg/L)	42	17.9±2.35	16.27±1.87	6.92	0.05
ORGNkg_ha	10 (mg/L)	42	11.30±1.28	15.77±3.07	24.71	0.05
ORGPhg_ha	35 (mg/L)	42	75.40±42.82	102.26±42.36	7.98	0.05

transported by surface and ground water predicts the high-potential agricultural areas. Globally, nutrient contamination is a very important aspect of water quality monitoring in rivers. In the Ruiru and Ndarugu rivers, the impact of nutrient contamination was evident especially where the rivers run near urban areas (Ruiru and Juja). Eutrophication is the most evident sign of nutrient contamination. In this study, high levels of both measured and simulated nutrients in the rivers suggest nutrient contamination. Water quality and balance can significantly be influenced by land use and land cover (Heathwaite & Heuvelmans *et al*., 2005; Abbaspour *et al*., 2007). When there in increased human activities, sources of organic nitrogen increase, including sewage from pit latrines and agricultural activities. In these watersheds, an increase in residential areas is observed in the lower reaches, where urban areas are expanding. This is expected to further have an impact on water quality parameters.

Steep slopes are observed as a major characteristic of both Ruiru and Ndarugu watersheds, particularly in the upper reaches. In many tropical areas, agricultural activities on steep slopes have been recognized as critical in degradation of watersheds. For example, in Jamaica, agriculture on steep slopes is the single most important factor for watershed degradation (Hayman, 2001). The high sedimentation levels in areas under forest could be attributed to steep slopes, forest degradation, and unsustainable agriculture in these areas. Although modelling results are only indicative, these processes should be further investigated.

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