

Spatio-temporal Effects of Land Cover Change on Water Quality Using SWAT Model and Geospatial Techniques in River Ruiru Watershed, Kenya

Ann Waithaka*

Department of Geography, Mount Kenya University, Kenya

*Corresponding author: Annwaithaka64@gmail.com

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Abstract This study aims to assess the effects of land cover change on water quality in River Ruiru watershed by integrating remotely sensed data, Geographic Information System and the Soil and Water Assessment Tool (SWAT) model. Landsat 5 TM 1984 and 8 OLI-TIRS 2017 images were categorized into seven land cover classes following a supervised image classification technique. The study findings indicate that built-up, annual crops and perennial crops areas increased by 1.83%, 15.05% and 10.90% respectively between 1984 and 2017. On the contrary, grassland, shrubland and forestland declined by 6.21%, 11.92% and 10.66% respectively. Consequently, findings from the study indicate that nitrates in the surface runoff (NO3SURQ), nitrates in lateral runoff (NO3LATQ), organic nitrogen (N.ORG) and organic phosphorus (P.ORG) increased from 0.05kgN/ha/yr, 0.06kgN/ha/yr, 5.77kgN/ha/yr and 0.87kgP/ha/yr respectively in 1984 to 1.47kgN/ha/yr, 0.19kgN/ha/yr, 70.60kgN/ha/yr and 8.86kgP/ha/year respectively 2017. This could be attributed to the expansion of agricultural areas both annual and perennial crops, increased use of inorganic fertilizers rich in nitrates and phosphorus, increased surface runoff from the cultivated lands and loss of natural land cover. As such, remedial actions to address the effects of land cover change on water quality both by the national and county governments are required. These may include agricultural best management practices and integrated water resources management.

Keywords: GIS, Integrated Water Resources Management, Nitrates, Organic Nitrogen, Organic Phosphorus, Remote sensing

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1. Introduction

Estimations suggest that humans have already transformed three-quarters of the Earth's surface, driven largely by expansions in urban and agricultural land use, and associated with significant losses of natural land cover in many regions [1,2]. As [3] note that most river basins have undergone massive change over the past years due to various land use activities. With over 41% of world's population living in river basins, there is a real cause of concern on the likely effects of human induced activities on the river basin's water resources [4]. As such, the relationship between land use and water quality has become a relevant topic of discussion, as anthropogenic activities in watersheds continue to increase [5].

River ecosystems are critical surface freshwater resources that play an indispensable role in human production and livelihoods, maintaining the security of flora and promoting sustainable development [6,7]. However, according to [8], world's major rivers are being extremely depleted and polluted, degrading and destroying

the surrounding ecosystems, thus threatening the health and livelihood of people who depend upon them for irrigation, drinking and industrial water.

Land cover changes have far-reaching implications for hydrological response, making them a critical consideration in watershed management and water resources management [9]. They have been recognized as a force of global concern, causing environmental degradation across various ecosystems [10,11,12,13,14]. These changes are the result of dynamic human-environment interactions in processes operating at different spatio-temporal scales [15,16].

In Africa, the deterioration of the quality of water resources due to land use changes has been increasing leading to severe health risks to both humans and ecosystems [17]. Land cover changes are very common in developing countries whose economies are mainly dependent on agriculture and with rapid human population growth [18]. The conversion of forestland, agricultural land, and wetlands to built-up urban land use can increase the area of impervious surfaces [19,20], which disrupts the natural hydrological conditions within the watershed by increasing the rate of runoff and sometimes nonpoint

source (NPS) pollution that affects hydrological quality [21,22].

Reference [23] posits that it is necessary to expand research efforts to establish the effects of land use and land cover change at various spatial scales on downstream waters and to observe how change in watersheds have affected stream conditions through long-term analysis. Therefore, future studies should incorporate the impacts of land cover change on stream water quality [24]. Additionally, Zeng et al. [25] conclude that a more comprehensive analysis of the effects of climate variables, land use and land cover changes and other water-related human activities is required in further work.

Land use changes in East Africa resulting from rapid urbanization and clearance of forests to create room for agriculture and settlement have emerged as main stressors of streams and rivers [26,27]. These changes have the potential to have a significant influence on water resources [28], mostly in regions where water availability is limited and could result in an increase in water scarcity thus leading to a deterioration of living conditions [29]. Therefore, quantitative assessment of the implications of land cover change on water quality is vital for basin environmental conservation as well as the long-term development and management of water resources [30].

According to the international standards, Kenya is categorized as a water scarce country with the currently available freshwater of 400 m³ per capita per annum in comparison to the 1000 m³ per capita per annum recommended by the United Nations [31,32]. Water resources in Kenya are gradually becoming polluted at point and non-point sources as a result of urbanization, agricultural and industrial activities [33]. This underscores the need to monitor the effects of land cover change on water quality in Kenya.

Management of water resources and land use patterns are inherently linked [34] and there has been an increased need for development and management of water resources in Kenya because of the increasing population as well as the country's increasing use of water for agriculture [35]. Moreover, evaluating the influences of land cover change on hydrological characteristics is key for understanding the effects of land cover change on hydrological processes over the Earth's surface [36] and managing and developing watersheds [37].

The Soil and Water Assessment Tool (SWAT) model is considered one of the best models to simulate how land cover change affects water quality and quantity and has been applied extensively worldwide [38,39,40]. It is widely acknowledged for its capacity to accurately mimic both the quantity and quality of rivers at different scales, ranging from local watersheds to large river basins. This makes it a valuable tool in addressing the demand for reliable hydrological models [41].

2. Materials and Methods

2.1. The Study Area

The study area was River Ruiru watershed which has an area of 484.515 km² [42]. The watershed has a population of 671,646 persons [43]. It lies between longitude 36°40'E

and 37°00'E and latitude 1°10'S and 0°50'S as shown in Figure 1. River Ruiru originates from Kikuyu plateau and drains to the southeastern slopes of the Aberdare ranges in Kiambu County.

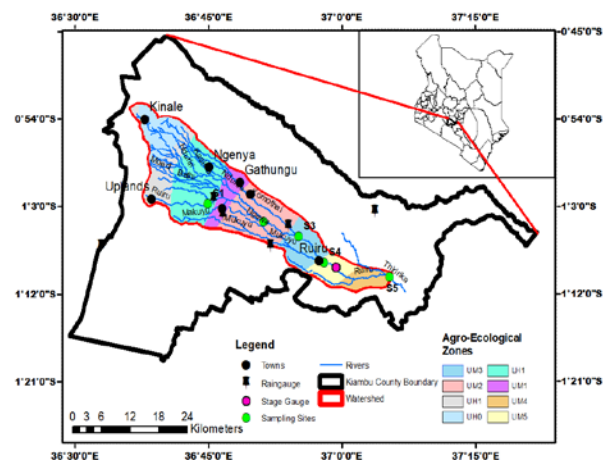


Figure 1. River Ruiru watershed

River Ruiru watershed is hydrologically located within the Athi Basin 3BC sub-basin administered from upper Athi Water Resource Authority (WRA) in Kiambu. The watershed is covered by a well distributed dense lateral river network. River Ruiru is the major river in the watershed with its main tributaries being Makuyu, Gatamaiyu and Komothai [44]. It is located in a medium rainfall potential area of Athi Basin with moderate and reliable rainfall. It has two distinct rainy seasons: The long rains experienced in March-April-May (MAM) and short rains experienced in October and November. It has four dominant land cover types which include trees, settlements, grasslands and croplands [45]. The land cover has high temporal variations with the wet season exhibiting high vegetation cover (high biomass) and the dry season exhibiting very low vegetation cover (low biomass). The upper part is predominantly forested but is currently threatened by encroachments into the forest area. Change in land cover patterns due to change of user from agricultural commercial enterprises to residential, peri-urban and urban settlements is the main cause of declining quality and quantity of water in the watershed. The area has an undulating landscape, with steep valleys where the rivers cross. It is also dominated by highly dissected ranges. The land use potential may be described according to the country's agro-ecological zones which may be categorized as medium to high potential falling under zones UM3, UM2, UH1, UH0, UM1, UM5, UM4 and LH1 (Figure 1) [46].

2.2. Data Acquisition

2.2.1. Land Cover Data

Land cover data of two Landsat TM and OLI/TIRS images for 1984, and 2017 were obtained from USGS-Earth explorer (<http://www.earthexplorer.usgs.gov/>) website in GeoTIFF. These Landsat images were selected based on the availability of cloud free landsat images, available SWAT input weather data for the study area and also a time interval that is long enough for land cover change to have measurable impacts on hydrologic

response. The selected images were taken during the dry seasons of the year to avoid uncertainties, clouds, and possible errors resulting from seasonal differences between time points (December-January-February-March). It has been suggested that by using images taken during the dry season will reduce confusion between dense forest vegetation and small-scale agricultural plots at forest edges [47,48].

2.2.2. Digital Elevation Model

Digital Elevation Model with a spatial resolution of 30m was obtained by the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) which was downloaded from USGS-Earth explorer website (<http://www.earthexplorer.usgs.gov/>). It was used for delineating the watershed spatial extent and stream network. It was also used during SWAT hydrological modelling.

2.2.3. Meteorological Data

Rainfall data from five ground-based weather stations and maximum and minimum temperature data from Thika Agromet station were acquired from Kenya Meteorological Department. Wind speed, solar radiation and relative humidity data were obtained from global weather data set of the National Centre for Environmental Prediction (NCEP) (<http://globalweather.tamu.edu/>) Climate Forecast System Reanalysis (CFSR). This data was used for weather data definition in SWAT model.

2.2.4. River Discharge Data

Mean daily discharge data in cubic meters (m^3s^{-1}) for Ruiru River was obtained from Water Resources Authority (WRA) in Kiambu for the period between 2007-2013 for the gauge station 3BC8 located in Ruiru Bridge. This data was used for calibration and validation of the SWAT model. The discharge data for the period from 2007-2013 was chosen as it was complete with no missing data.

2.3. The SWAT Model Set up

The effects of land cover change on water quality were assessed by integrating remotely sensed data, Geographic Information System and the Soil and Water Assessment Tool (SWAT). The SWAT is a versatile model currently used worldwide to evaluate water quality and hydrological concerns in a number of varying watershed scales and environmental conditions [49] for abreast policy decision making and effective watershed management. The integration of SWAT with GIS and remote sensing tools is helpful in analysing and evaluating spatio-temporal land cover dynamics [50,51]. ArcSWATv2012.10.1.18 was downloaded from the SWAT model website (<http://swat.tamu.edu/software/arcswat>) and installed in ArcGISv10.4.1.

Two independent SWAT runs were carried out on a monthly basis based on the 1984 and 2017 ArcGIS generated land use maps. The following hydrological characteristics were compared for the two years; nitrates in the surface runoff (NO_3SURQ), nitrates in lateral flow (NO_3LATQ), organic nitrogen (N.ORG) and organic

phosphorus (P.ORG).

3. Results

3.1. Land Cover Types for 1984 and 2017

Findings from the study indicate that built-up areas increased by 1.83% from 1.9% to 3.8%, annual crops (mixed farming) increased by 15.05% from 31.6% to 46.6% while perennial crops (Tea and Coffee farming) increased by 10.90% from 5.3% to 16.2%. Area under water bodies also slightly increased by 0.095% from 0.22% in 1984 to 0.31% in 2017. On the other hand, grassland declined by 6.21% from 11.3% to 5.1%, shrubland declined by 11.92% from 13.0% to 1.4% while forestland decreased by 10.66% from 36.7% to 26.6% as presented in Figure 2.

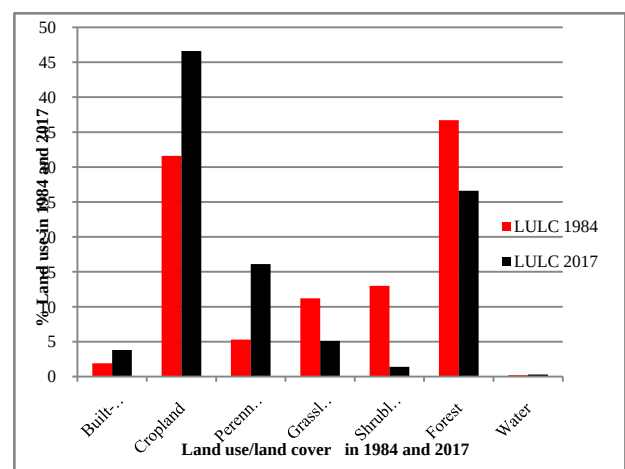


Figure 2. Land cover change between 1984 and 2017

3.2. Effects of Land Cover Change on Water Quality

The results of the study indicate that changes in land cover between 1984 and 2017 led to a change in water quality of River Ruiru watershed. The nitrates in the surface runoff (NO_3SURQ), nitrates in lateral runoff (NO_3LATQ), organic nitrogen (N.ORG) and organic phosphorus (P.ORG) increased from 0.05kgN/ha/yr, 0.06kgN/ha/yr, 5.77kgN/ha/yr and 0.87kgP/ha/yr respectively in the year 1984 to 1.47kgN/ha/yr, 0.19kgN/ha/yr, 70.60kgN/ha/yr and 8.86kgP/ha/year respectively in the year 2017. This could have been attributed to the expansion of agricultural areas both annual and perennial crops, increased use of inorganic fertilizers rich in nitrates and phosphorus, increased surface runoff from the cultivated lands and loss of natural land cover.

Similar observations were reported by [52] in a study on the effects of land use change on water quality in Eerste River in South Africa who observed that from the year 1985 to 2015, the forest cover decreased from about 15% to about 10% and from about 8% to 2% between 2010 to 2015, while settlements increased from 38% to 55% from 1985 to 2015. Bareland decreased from 8% to 3%. This study indicated a significant correlation ($p < 0.05$)

between water quality and land use changes. Equally, Calijuri et al. [53] in their study on the impact of land use/land cover changes on water quality and hydrological behaviour observed that the changes that occurred in land use/land cover for the development of current agriculture significantly impacted the hydrological behaviour in the Alto Paraguacu watershed. Similarly, Hossain [51] evaluated the relationship between land use change and water quality and found that stream water quality changed with land use practices and expansion of agricultural land is one of the major cause of stream water pollution.

Equally, Huang et al. [54] while studying the relationship between the proportion of land use types and water quality in the Chaohu lake basin indicated that built-up land was largely positively correlated to the indicators of water quality and the forest land, grassland and water areas were negatively related with water quality variables. The built-up areas were positively related to total phosphorus and total nitrogen. Similarly, research results by [55] in a study on the effects of land use/land cover on water quality of low stream order in Southeastern Brazil indicated that forest cover played a significant role in keeping water clean, while agriculture and urban areas led to water quality degradation. Reference [56] found that land use changes had important effects on reducing water quality of Karkheh River in their period of study. Correspondingly, Chotpantarat & Boonkaewwan [57] in their study on the impacts of land use/cover change on watershed discharge and water quality in Thailand concluded that changed land use was closely associated with the quantity of $\text{NO}_3\text{-N}$ and PO_4^{3-} .

Likewise, Namugize et al. [58] in their study on the effects of land use /land cover change on water quality in the uMngeni river catchment in South Africa observed that natural vegetation, forest plantation and cultivated areas occupied 85% of their study catchment. While cultivated areas, built-up areas and degraded areas increased by 6%, 4.5% and 3% respectively, they coincided with a decrease in natural vegetation by 17%. This led to variability in the concentration of water quality parameters from 1994-2011 and an overall decline in water quality was observed. Equally, Li et al. [59] observed that during 2006-2013, corn and soybean cultivation in the basin area increased by 62% and 18% whereas cultivation of spring wheat, forest and pasture decreased by 30%, 18% and 50%. These changes in cultivation increased total phosphorus by 14.1%, nitrate by 5.9% and total nitrogen by 9.1%. Similarly, Permatasari et al. [60] in a study on the effects of land use change on water quality in Celiwung watershed concluded that land use change had great impact on water quality and the rising urban land from agricultural land had a positive correlation with increasing concentration of pollutants in the river.

Similarly, Peterson et al. [61] in their study on the effects of land use change on streamwater quality of a coastal catchment demonstrated the link between land cover/land use and water quality in Touws and Duiwe river catchments. Agriculture intensified rapidly in the Duiwe river catchment making concentrations of nutrients and electrical conductivity to be higher than in the more natural Touws river catchment. Furthermore, Zamani et al. [62] in their spatial analysis showed that within four

decades about 980 hectares of forests in Ziarat catchment in Iran were converted to other classes of land cover/land use-about 67% to croplands, 8.5% to residential, 13% to bare lands and 11.5% to roads. The results of the research showed that land use/land cover change was one of the key factors causing water quality changes in the study area. Equally, Chattopadhyay et al. [63] in a study on water quality variations as linked to land use patterns in Chalakudy river basin observed that correlation analysis of various parameters indicated seasonality in physico-chemical characteristics of river water which was linked to fluctuations of drainage discharge and changes in land use pattern.

4. Conclusions

River Ruiru watershed has experienced land cover change between 1984 and 2017 which has had effects on the water quality. The increase in built-up areas, annual crops and perennial crops and the decline in grassland, shrubland and forestland led to an increase in the nitrates in the surface runoff (NO_3SURQ), nitrates in lateral runoff (NO_3LATQ), organic nitrogen (N.ORG) and organic phosphorus (P.ORG) due to the expansion of agricultural areas both annual and perennial crops, increased use of inorganic fertilizers rich in nitrates and phosphorus, increased surface runoff from the cultivated lands and loss of natural land cover. As such, remedial actions to address the effects of land cover change on water quality both by the national and county governments are required, especially in the face of growing human impacts on the environment. These may include agricultural best management practices and integrated water resources management.

Conflict of Interest

The author declares there is no conflict.

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