Application Of Hydrological Models In Poorly Gauged Watersheds: A Review Of The Usage Of The Soil And Water Assessment Tool (SWAT) In Kenya

Wambugu Mwangi, Nyandega Isaiah, Kıthiia Shadrack

Abstract: In water-scarce developing countries, river basins are some of the most valued natural resources, but many are poorly gauged and have incomplete hydrological and climate records. In the recent years, tropical rivers are increasingly becoming erratic, with many hydrologists attributing this variability to combined effects of landscape-specific anthropogenic activities and climate change. Uncertainties about the impacts of climate change compound the challenges attributed to poor and often inconsistent river monitoring data. Under data-scarce conditions and with the increasing land use intensification and urbanization, modelling approaches become a useful tool in planning and management of water resources. In this paper, we review the application and usability of the Soil and Water Assessment Tool (SWAT) model in conventional planning practice in the management of water resources is poorly-gauged tropical watersheds of Kenya. We assess the technical implications of the model in Intergrated Water Resources management (IWRM) and its applicability as a planning and management tool for water resources in the era of climate change.

Index Terms: Climate change, Hydrological Models, Land use, IWRM, planning, SWAT, watersheds

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1 Introduction

MANY national Water Resources Management Authorities have developed policies that are aimed to support decision making in water resources management [1]. Professionals in the water sector are therefore increasingly using models as tools in decision making, particularly because they provide a cost-effective way of simulating hydrological processes, including sediment, nutrients and pesticide production and transport [2]. Models have been gaining popularity for their capability to simulate different scenarios of water availability, including climate changes [3], [4]. In water resource planning and management, the understanding of hydrologic response of watersheds to land use and climatic factors is an important component [5]. Land use change is particularly an important factor: 75 million hectares of forest were converted to agriculture and pasture between the years 1990 and 2015, and 20 million hectares of original forest were lost, with the remaining forest being fragmented and continually under threat from human activities [6]. The impacts of changing climatic patterns have become a key concern for many sectors, including river basin hydrology. This is because land use impacts are interlinked with impacts of climate change [4]. In Africa, observed climatic changes include warming of 0.7^{o}C over the 20th century, 0.05^{o}C warming per decade and increased precipitation for East Africa. The Intergovernmental Panel on Climate Change (IPCC) project predicts a warming from 0.2 ◦C (low scenario) to more than 0.5 ◦C per decade (high scenario), 5–20 % increase in precipitation from December-February (wet months) and 5–10 % decrease in precipitation from June–August (dry months) [7], [8]. The overall annual mean rainfall in East Africa is projected to increase during the first part of the century [9]. The East African region continues to be one of the fastest growing regions in Africa, with 6% growth rate in 2011 [10]. Availability of surface water to sustain this growth is critical as it is central to the development of agriculture, industry, power generation, and other important economic activities. The region has a population of 160 million people [10], and rainfall distribution and intensity varies depending on the region. Some parts of East Africa experience prolonged drought periods, such as the coast of Somaliland and Puntland which may experience many years without any rain [11]. In other parts, rainfall generally increases towards the south and with altitude, being around 400 millimeters at Mogadishu and 1,200 millimetres at Mombasa on the coast. Towards the inland, rainfall increases from around 130 millimetres at Garoowe to over 1,100 millimetres at Moshi near Kilimanjaro. Most of the rain falls in two distinct wet seasons, one centred on April and the other in October or November[11]. Despite this, water stress is an important factor in this region, with Tanzania and Ethiopia ranked to be amongst the most water-stressed countries in the region by 2040 [12]. One third of the world's population lives in countries where there is moderate to high water stress [13]. Kenya is classified as a chronically water-scarce country with its natural endowment of freshwater limited to an annual renewable supply of only 647 cubic meters per capita [14]. A country is categorized as water scarce if its annual water supply is less than 1,000 cubic meters [14]. Kenya is one of the 31 countries predicted to run short of fresh water resources by the year 2025 [14]. The growing human population, nearly 50% of who live below the absolute poverty line, puts increasing available freshwater resources [15]. Water resources availability in Kenya also varies significantly in time and between regions. Most parts of the country have two rainy seasons; the long rains from March to May and short rains from October to November. The average annual rainfall is 630 mm, but it varies between less than 200 mm in northern Kenya to over 1,800 mm on the slopes of Mount Kenya. Every three to four years, Kenya experiences droughts and floods, which affect major sectors of the economy [16]. In order to

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effectively plan and manage the scarce water resources in the country, there is need for reliable information on hydrology of river systems. However, most Kenyan catchments lack robust systems of monitoring watersheds and have limited current and historical river hydrology data. The use of modelling approaches is therefore a reasonable approach for simulation of water quantity and quality under changing land use and climatic patterns. The Soil and Water Assessment Tool (SWAT) is a semi-distributed model 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 of time [17]. Several studies have applied the model in Kenya to simulate flow regimes under different scenarios of change. However, their application in practical scenarios in watershed management has not been documented. Because of the availability of free datasets required to run the model, it can be used to simulate critical water resource management problems. This paper reviews the practical application of the SWAT model in Kenya.

2 HYDROLOGICAL MODELLING OF WATERSHEDS

Human activities contaminate surface waters in two ways: (a) through point sources, such as sewage treatment discharge and storm-water runoff; and (b) by non-point sources such as runoff from urban and agricultural areas [18]. Non-point sources are especially difficult to detect since they generally encompass large areas in drainage basins and involve complex biotic and abiotic interactions [19]. Natural catchment characteristics such as topography and surficial geology and the biochemical processes in the terrestrial environment can influence the hydrochemical response of [20]. Surface runoff, especially under the first flush phenomena, is an important source of non-point source pollution, and may be enriched with different types of contaminants under different land use [21]. For example, runoff from agricultural lands may be enriched with nutrients and sediments, while runoff from urban areas may be enriched with rubber fragments, heavy metals, sodium and sulphate from road networks [22]. Several hydrological processes, such as evapotranspiration, interception, infiltration, percolation and absorption, coupled with different types and extent of vegetative surfaces can modify the land surface characteristics, water balance, hydrologic cycle, and the surface water temperature [23]. These processes affect the quantity of water available for runoff, streamfow and ground water flow, as well as the physical, chemical and biological processes in the receiving water bodies. There is therefore a strong relationship between land use types and the quantity and quality of water. Several studies have shown that there is a strong relationship between land use types and water quantity, quality. For example, in a study of the effects of forested, agricultural and urban areas on water quality and aquatic biota in the Piedmont ecoregion of North Carolina, Fisher et al. [22] also noted a higher amount of nitrogen, phosphorus and Fecal coliform bacteria in the poultry production areas in the Upper Oconee Watershed in Georgia. In another study of Coweeta Creek in western North Carolina, Bolstad and Swank [23] observed that there were consistent changes in water quality variables, concomitant with land-use change. Therefore, changing land use and land management practices are regarded as one of the main factors in altering the hydrological system, causing changes in runoff, surface water supply yields, as well as the quality of receiving water. Although there have been some studies on the impacts of land use on water flows and quality, the complex intrinsic relationships of land use, water yields and water quality in different geographical areas under different scales are yet to be elucidated. Watershed management and catchment scale studies have become increasingly more important in determining the impact of human development on water quality both within the watershed as well as that of the receiving waters, they still leave many questions unanswered. For example, there is still an ongoing dispute regarding whether the land use of the entire catchment or that of the riparian zone is more important in influencing the water quality, all other factors remaining constant [24]. These uncertainties remain partly because each catchment has a unique combination of characteristics that influence water quality, and partly because thorough investigations at the watershed scale are extremely time and resource consuming [24], [25]. Several methods have been developed to study the implications of climatic changes on hydrological processes such as the paired catchments approach, time series analysis (statistical method), and hydrological modelling [26]. Among these approaches, hydrological modelling has widely been applied throughout the world as it requires fewer resources and provides more flexibility [27]. Other studies have assessed the hydrologic response to Land use and Land cover (LULC) changes with different LULC distributions, and tested the model performance for changing LULC was in an artificial watershed with one crop at a time and one under-lying soil type to eliminate the complex interactions of natural watersheds [28] Effective analytical tools, such as geographical information systems (GIS) and multivariate statistics, are able to deal with spatial data and complex interactions, and are coming into common usage in watershed management [29]. However, their effectiveness depends on the quality and quantity of data collected in the field, which tend to be sparse, especially when dealing with entire watersheds [30] Watershed models simulate hydrologic processes in a holistic approach by incorporating of the watershed area compared to other models which primarily focus on individual processes or multiple processes within a water body without full incorporation of watershed area [31]. Watershed models were developed in the period between 1960 and 1990, including: HEC-1, developed in 1967 at the Hydrologic Engineering Center in Davis, CA [32] ; the Hydrologic Simulation Program in Fortran (HSPF) in the 1960's [33]; TOPography based hydrological MODEL (TOPMODEL) in 1974 [34] ; and Soil and Water Assessment Tool SWAT [17] . The release of these models was followed by improvement on data management and utilization [35] through graphical user interfaces (GUIs) with geographic information systems (GIS) and the use of remotely sensed data [36].The trend in watershed modelling has been influenced by advancements in GIS and remote sensing techniques [37]. These include remote sensing techniques such as radar and satellite imaging, which are used to obtain spatial information on land use and soil type at regular grid intervals with repetitive coverage. GIS technology has provided hydrologists with further capabilities in reducing computation times, efficiency in handling and analyzing large databases that describe heterogeneity in land surface characteristics, and improving display of model results [37]. Early GIS software packages existed as isolated software programs with minimal functionality, unsophisticated user interfaces and limited processing capabilities; which was influenced by fairly simple operating systems that possessed minimal flexibility, making these systems difficult to manipulate [37].

2.1 The Soil and Water Assessment Tool (SWAT) Model

SWAT is a semi-distributed model 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 of time [17]. The model is based on the hydrologic cycle, which is centered on the water balance equation:

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - W_{deep} - Q_{day}) \quad (1)$$

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 [17] [38]. 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 [39]. 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 model 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 [39]. The data types and examples of sources are shown in Table 1.

TABLE 1

Data Types and Examples of Sources for SWAT Model

Data Type	Example of Sources
Digital Elevation Model (DEM)	Shuttle Radar Topography Mission (SRTM)
Land use/land cover map	Classification of Satellite Imagery (e.g. Landsat) 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	National/ Regional Meteorological Organizations Climate Forecast System Reanalysis (CFSR): http://globalweather.tamu.edu/
Measured Streamflow	Water Resources Management Authority, Kiambu Regional Office.

2.3 Global Applications of SWAT in Water Resources Management

Arnold and Fohrer [40] documented the applications of SWAT model globally, with the USA taking lead in several practical applications of SWAT. According to Arnold and Fohrer, most of the applications in USA focus on two major aspects: (a) land use change and management and; (b) climate change on water supply and water quality. Several federal government institutions in the USA have embraced SWAT in their operations, including Environmental Protection Agency (EPA), Natural Resources Conservation Service (NRCS) and National Oceanic and Atmospheric Administration (NOAA). SWAT has also achieved acceptance in other parts of the world for several applications, incorporating themes such as water balance, Sedimentation, Phosphorus cycle and Nitrogen cycle [40].

3.2 Water Resources Management Scenario in Kenya

Most countries in sub-Sahara Africa face severe challenges in securing sustainable access to quality water to meet the increasing demands of a growing population and socio-economic development, while preserving the essential watershed ecosystems on which water resources depend [41]. In these countries, water resources development lacks crucial infrastructure for provision of information and data on the status of renewable water resources, which further complicates water planning and governance. As such, modeling approaches would offer a great potential in these countries as they have gained interest in water-scarce watersheds, and continue to draw attention especially in poorly gauged basins. Several studies have shown that watershed models can accurately predict hydrological processes in poorly gauged and unmonitored watersheds [4].

3.3 Application of the SWAT Model in Kenya

Table 2 and Fig 2 summarizes main publications on SWAT applications in Kenya. These studies focus on calibration uncertainty, runoff and sedmentation, land use, climate change, water quality, swat development and environmental policy.

Table 2: *Applications of the SWAT Model in Kenya*

	Calibration uncertainty	Runoff and sedimentation	Land use	Climate change	Water Quality	SWAT development	Environmental policy
Le and Pricope (2017)		X				x	
Omwoyo et al (2017)				x			
Musau et al., (2015)				x			
Musau et al (2014)	X						
Baker and Miller (2013)			x				
Dessu and Melesse (2012)		X					
Mango et al (2011)			x	x			
Odira et al (2010)			x				
Githui et al (2009a)				X			
Githui et al (2009b)		X	x				
Jacobs et al (2007).		X					x
Jayakrishnan et al., (2005)							
Wambugu et al (unpublished)			x		x		

3.3.1 Land use

Most of the SWAT studies in Kenya have focused on the impact of land use practices on hydrological processes. Amongst the earliest SWAT applications in Kenya include a study by Jayakrishnan et al. [42] which applied the model to study effect of land use change associated with dairy farming on the streamflow and sediment transport of the Sondu River basin which drains 3050 km^2 of land to Lake Victoria in Kenya. The study indicated that the monthly simulated discharge of existing land use “compares well” to the observed value and reported a Nash–Sutcliff efficiency (NSE) [43] of 0.1. This study emphasized the need for development of better model input data sets in Africa, which are critical for detailed water resources studies. Githui et al. [44] used SWAT in the Nzoia watershed, western Kenya, to examine the impacts on base flow and streamflow under prevailing land use change trends (e.g., forest conversion to smallholder agriculture) versus afforestation, and found out that flood risks were exacerbated if existing land use change trends were to continue. The study revealed a strong relationship between the impact of changing land use (especially increasing in agricultural land use) the hydrological regime of the Nzoia River catchment in Kenya. Increased runoff in Nzoia catchment was attributed to an increase in agricultural land use and a corresponding decrease in forest cover between 1973–2001, with SWAT simulations reporting increased runoff by about 119% between 1970 and 1985 [44]. In another study, Mango et al. [4] used SWAT coupled with satellite-based estimated rainfall to support water resources management efforts in the Mara River Basin, demonstrating that in data scarce regions such Kenya, it is possible to approach water resources challenges using modeling approaches. Although the study emphasized that can be a challenging undertaking in data-scarce regions, it demonstrated that the SWAT model can provide fair results that that can be used to explore land use impacts and inform watershed interventions. The study, however, cautioned that such models may be impeded by uncertainties, including processes unknown to the modeler, processes not captured by the model and simplification of the processes by the model [45]. The study concluded that any further forest conversion would reduce dry-season flows and intensify peak flows in the watershed, further exacerbating already serious problems related of water scarcity in dry periods and hillslope erosion during the wet season. Baker and Miller [46] used the SWAT model to identify the spatial and temporal dynamics of magnitude and direction of land use change in the River Njoro watershed in Kenya. This study showed that land use changes in River Njoro Watershed led to a shift to increased surface runoff in the uplands coupled with decreased groundwater recharge. The study attributed deforestation of the Mau Forest to increased erosion and sedimentation as a result of flashier flows and increased streamflow. The importance of a healthy watershed was highlighted by this study, because upstream conditions have a direct impact on downstream ecology (e.g. River Njoro feeds into Lake Nakuru, an important National Park in Kenya and a world renown Ramsar Site supporting diverse wildlife populations and birds). The study identified a potential increase in conflict over dwindling water resources, especially between agricultural and pastoral communities within the watershed. Odira et al simulated streamflow changes as a result of the land use land cover changes using the SWAT model in Nzoia watershed in Kenya and reported increased discharge during wet months and a decreased discharge in the dry periods [47].

3.3.2 Runoff and sedimentation

Dessu and Melesse [65] used the SWAT model for long-term rainfall–runoff simulation in the Mara River Basin on the border of Kenya and Tanzania. Like most watersheds in Kenya, the Mara River Basin is highly threatened by multiple watershed-level threats, including agricultural expansion, deforestation, human settlement, erosion and sedimentation, flooding and low flow. As such, this study utilized the SWAT model to understand the interaction among the natural processes and human activities in the basin. Although the study was limited by scarcity of observed data, the study showed that in the absence/limitation of rainfall data, alternative sources of data, such as satellite rainfall estimates (RFEs) can be used to run the model and produce acceptable results. Previous studies in the same basin [62], [66] applied SWAT on two tributaries in the Mara River Basin (Nyangores and Amala) combined rain gauge data and satellite RFEs to assess the effect of land use change using SWAT and reported that RFE performed better than rain gauge rainfall records. However, the authors indicated that the quality of rain gauge data may have contributed to these observations, which further justifies the use of alternative data sources such as RFEs.

3.3.3 Water Quality

Wambugu [49] (unpublished data) used the SWAT model to assess the impacts of land use practices on water quality on Ruiru and Ndarugu watersheds in Central Kenya. Available long term monthy monitoring data for the two monitoring stations on these rivers spanned a total four years, and was often incomplete due to varied reasons, including non-functional equipment. In this study, increased precipitation between 2011 and was shown to have significant implications on the hydrologic processes. Climate variability is an important factor to be considered for controlling basin hydrologic processes [50]. 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 was consistent with expectations in the Ruiru watershed but highly dynamic in Ndarugu watershed (Fig 1). Land use patterns have been shown to lead to impacts on stream flow processes [50]. Typically, an increased urban landscape would lead to an increase in stream flow. In this study, there was 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 were observed 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 becomes significant.

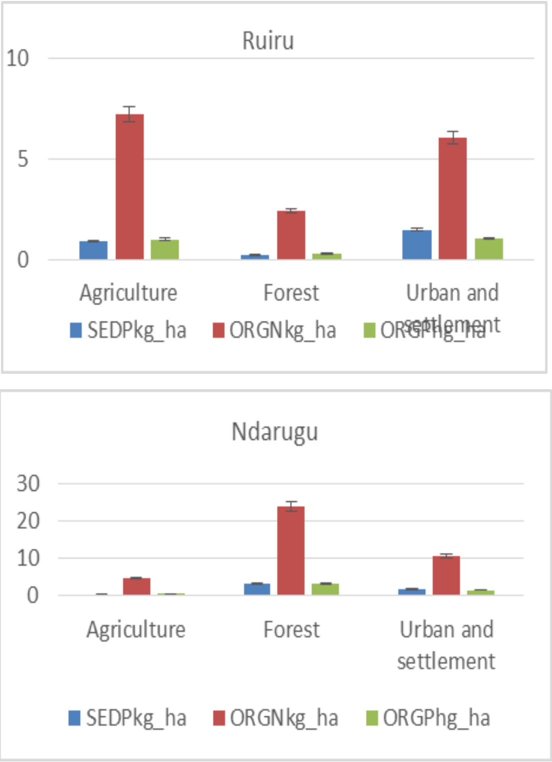

Fig. 1. *Simulated levels of sediment loading, organic nitrates and organic phosphates in agriculture-dominated, forest-dominated and urban/settlement dominated sub basins in Ruiru and Ndarugu Watersheds, Kenya.*

3.3.3 Environmental policy

In recognition of the critical need to address the impacts of deforestation on watershed processes, Jacobs et al [51] used the SWAT model to predict the impacts of land use on the Masinga Reservoir in Kenya. The Masinga Reservoir serves as a storage reservoir on Masinga Dam, which is one of the so called “seven forks” along River Tana, the longest river in Kenya. Masinga Dam and its reservoir are used for power generation, and it’s one of the most important dams in Kenya [52]. Because of sedimentation, it is estimated that complete siltation of the Masinga reservoir will occur within 65 years unless some type of intervention is undertaken [52], which is expected to drastically reduce the lifespan of Masinga dam (earlier estimated to reach upwards of 500 years prior to its construction). Jacobs et al therefore focused on the land use interventions on reforestation of the upper reaches of the catchment as a basis to provide improved catchment hydrology and water quality by reducing sediment and runoff into the lower portions of the Tana River basin. The authors intergrated an economic model with SWAT to develop to analyze the economic benefits and associated costs with establishing a green payment program in the Tana River basin. Further details of the study are discussed in section 3.4 on practical applications of SWAT model in Kenya.

3.3.4 Climate Change

Musau et al [3] forced the SWAT model with monthly temperature and precipitation change scenarios for the periods 2011–2040 (2020s), 2041–2070 (2050s) and 2071–2100

(2080s) to simulate the impacts of climate change on hydrological process in the upper Nzoia basin, Kenya. This study efficiently captured the historical hydrological processes in the upper Nzoia Basin based on the observed meteorological data and can therefore be applied in understanding of the dynamic water balance processes in this area. The study reported large that there are expected to be large uncertainties in the future precipitation, temperature and streamflow with significant implications on development and ecosystems in the watersheds and downstream areas. Under the current climate change uncertainties, this study provides useful insights for long-term basin-wide strategic planning and implementation of development projects, disaster preparedness and water resources management in this important basin. Omwoyo et al [53] used SWAT to simulate streamflow response under changing climate for the Upper Ewaso Ngiro Catchment in Kenya. The study generated temperature and rainfall climate change scenarios for representative concentration pathway 4.5 and 8.5 from 2021-2080 relative to the baseline period 1976-2005. Simulated streamflow varied between periods in different scenarios, with March-May showing a decrease (-26 to -10%) and June-February an increase (9-114%). Generally, the study reported streamflow response to be sensitive to changes in rainfall, and placed emphasis on water conservation and catchment management strategies such as agroforestry, afforestation and reforestation.

3.3.5 Calibration Uncertainty

As with most hydrological models, efficient estimation of optimum parameters is inevitable is inevitable to accurately estimate hydrological processes. Musau et al [54] applied the HydroPSO R package to SWAT model in R software to assess parameter identification and calibration in Nzoia Basin, Kenya. In this study, fourteen parameters representing the surface flow, subsurface flow and channel routing components of the water balance were selected for model optimization. The study demonstrated that the SWAT model can effectively simulate streamflow and can be successfully combined with R software to harness the combined benefits of a distributed hydrological model and flexible computing capability of the open source R software. However, the authors acknowledged that model error and input data are major sources of uncertainty in hydrological modelling.

3.3.6 SWAT development

Le and Pricope [55] recognized that Hydrologic models are an increasingly important tool for water resource managers as water availability dwindles and water security concerns become more pertinent in data-scarce regions. The study piloted the incorporation of the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) dataset into SWAT as an alternative to conventionally available climate datasets to assess its applicability in Nzoia basin of Kenya, a data scarce region. The CHIRPS dataset provides quasi-global high resolution precipitation information derived from a blend of in situ and active and passive remote sensing data sources. The study concluded that the CHIRPS dataset is only suitable for relatively flat, poorly gauged, small-scale watersheds and with an understanding of its limitations, but can also be used in SWAT to inform water resource management strategies in data scarce regions.

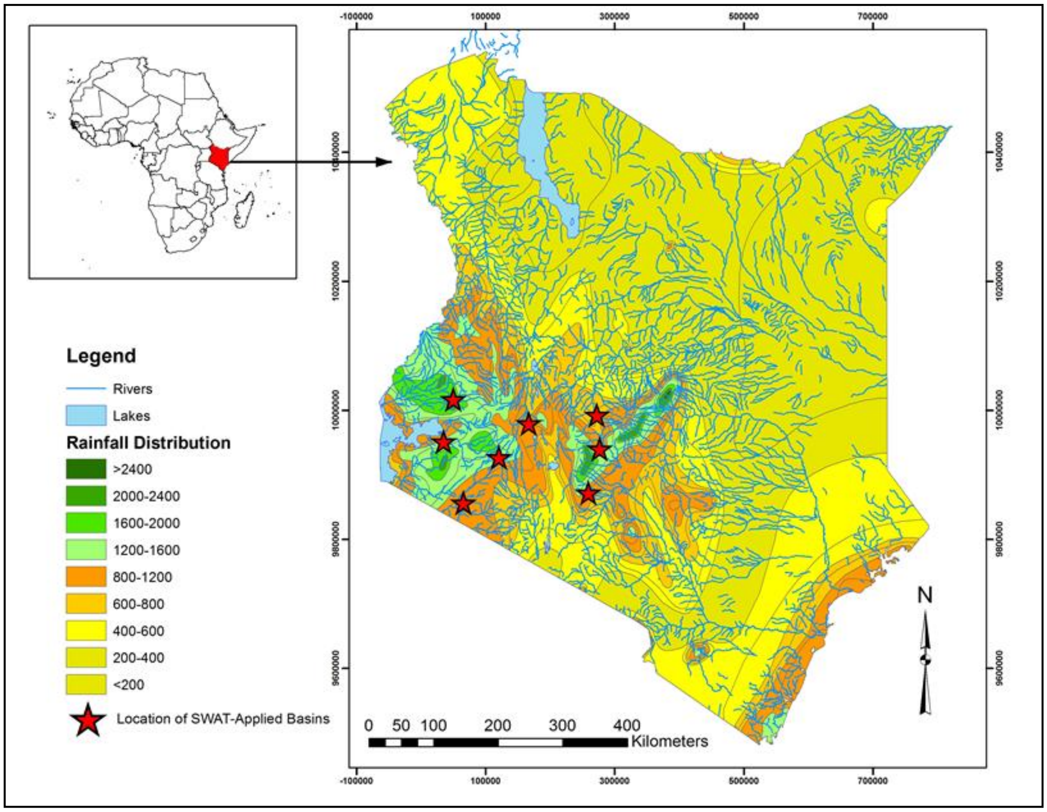

***Fig 2:** Location of SWAT-applied basins in Kenya.*

3.4 Practical Application of SWAT model in Kenya

Two studies showed evidence of practical applications of the model in water resources management. Mango et al. [4] [56] used SWAT to support water resources management efforts in the Mara River Basin. This study demonstrates that it is possible to use models to approach water resource challenges in data scarce regions in Kenya. In another study, Jacobs et al [51] used SWAT to evaluate alternative reforestation scenarios in the upper Tana basin, one of the most important basins in Kenya. The authors used an economic model to determine the opportunity costs associated with reforestation and the economic incentives, including green payments, which would be required to induce upper catchment users to engage in reforestation activities. The study found that reforestation activities would decrease sediment loading in the Masinga Reservoir (used for electricity generation) by 7 percent. This study provided practical scenarios for green payments (including specific amounts of money that users in the upper catchment would be paid for each ton of sediment retained in their farms), but also indicated that such benefits were beyond the capacity of downstream users to sponsor green payments.

4 CONCLUSIONS

Although hydrologic analysis of watersheds is a tedious process, models offer an attractive alternative to provide an analysis of watershed-scale hydrological processes and provide information that can be used for water resources management. Local, regional and national-scale water resources management strategies can employ hydrological modeling as decision support tools for sustainable domestic, agricultural and industrial water supply, as well as protection of the environment from the negative impacts of developmental activities. The SWAT model offers a valuable tool for such applications. Because of the heterogeneous nature of watersheds and their varying spatial scales, models like SWAT require a range of inputs for them to explicitly simulate hydrologic processes. This poses a challenge in developing countries like Kenya where hydrological data is often lacking or erratic. However, alternative sources of data, such as satellite-based RFEs, can be used as model inputs, with assumptions, to provide information on basic hydrological processes. Many hydrological models, including SWAT, run in a Geographical Information System (GIS). Besides playing a major role in developing model inputs (e.g. digital geospatial databases), they play a crucial role in visualizing the hydrological processes in form of maps. This implies that water sector professionals in data scarce regions require substantial skills in GIS to accurately and effectively run the SWAT model. Often, few professionals possess these skills in Kenya, which might limit the number of professionals using the model as a decision support tool. Although most of the studies reviewed used SWAT for academic and research purposes, two studies employed the model for practical purposes, indicating that the model has potential to be used as a decision support tool in Kenya. However, a common feature in all the studies reviewed is data scarcity, prompting researchers to use alternative data sources. Data availability is perhaps the most important impediment attributed to the relatively low number of studies and practical applications of SWAT in Kenya. Even when alternative data sources are used, model results varied widely, from poor performance to satisfactory results. Similar sentiments have been expressed elsewhere e.g. Adriolo et al. [56], who cited data scarcity as a limitation for effective utilization of the model. In Brazil, Garbossa et al [78] reported that the challenge to use SWAT is how to obtain enough data to simulate a watershed and lack of sufficient skills amongst professionals in environmental government departments and watershed committees. Where models such as SWAT are effective, caution should be taken to effectively validate the models to ensure that simulated scenarios are as realistic as possible. 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 national governments to upscale their efforts to have more sustained hydrological data is of utmost importance.

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