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Estimation of Basin Water Balance Components Using SWAT Model, In South Africa

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Abstract - This study is aimed at evaluating the impacts of land use land cover (LULC) changes on the availability of water balance components for a period of 28 years (1990-2018). To realize this objective, the Soil and Water Assessment Tool (SWAT) was utilized for the simulation of streamflow. The inputs used in SWAT were the digital elevation model (DEM), LULC maps for 1990 and 2018, soil maps, and slope data created using the ArcGIS spatial analysis tool. A three-year warm-up period was used. The results show that there was a rise in LULC within 28 years. The analysed LULC changes in 1990 showed that the least dominant classes were water and barren land, the most dominant were pasture and residential, followed by forest mixed, which accounted for 71.44%, 16.73%, and 5.50% of the total area, respectively. However, the analysed LULC changes for 2018 showed the most dominant to be pasture, followed by residential, and agricultural land-generic, comprising 65.08%, 18.82%, and 7.96%, respectively. In addition, the hydrology model outputs from 1990 and 2018 were compared, resulting in changes in evapotranspiration, surface runoff, lateral flow, and percolation of -0.7mm, 4.24mm, -3.39mm, and -0.13mm, respectively. This study identifies that LULC changes result in heightened surface runoff due to impervious surfaces, deforestation, and drainage, leading to increased flood risk and soil erosion. The reduction in evapotranspiration, lateral flow, and percolation impacts modified climate, diminished cooling, decreased baseflow in rivers and streams, and lower groundwater recharge. These results suggest that there's a relation between LULC changes and their impact on the water balance of the catchment. Therefore, more studies should be done on this catchment to assess the potential effects of other water balance components, such as a possible increase in abstraction, groundwater, and climate change, on the runoff.

***Keywords*:** Land use land cover (LULC); Agricultural land generics; Surface runoff; Pasture, Soil and Water Assessment Tool (SWAT), Calibration, and Validation.

1. Introduction

Water is a scarce resource in South Africa, according to reports [1], and the country is under water stress. Furthermore, according to [2], South Africa is a country with water stress because it only gets 492 millimeters of rain annually despite evaporation exceeding 2000 millimeters annually. According to [2], South Africa has a freshwater shortage because of declining water quality brought on by ongoing pollution activities and the destruction of river catchments [3]. Notably, urbanization, deforestation, river damming, and wetlands destruction are the main causes of declining water quality [2], [4].

In light of the aforementioned, it is crucial to recognize that the destruction of river catchments has had an impact on land use, which has changed over time, and that these changes have had a complex impact on water as a resource [5]. For instance, increased transpiration, increased interception, and decreased soil moisture caused by afforestation typically alter the water cycle, negatively impacting the moderate catchment water balance [1]. The impact of land-use change in a watershed affects the water supply by changing hydrological processes like runoff, baseflow, groundwater, and infiltration, according to [6], [7]. The natural hydrologic conditions of the catchment may also change because of changing land use patterns [8].

LULC change is linked to the intensification of agriculture, and urban development, and may significantly impact hydrological processes in small watersheds and at a regional scale [9]. It is also worth highlighting that the activities on the C81F quaternary catchment are mostly subsistence and commercial farming, which require more water for irrigation purposes [10]. Since the study area is mountainous, the upstream part receives more rain and the downstream receives less [11]. Despite this, the whole area needs water to sustain its various activities [12]. However, the impacts of water unavailability are attributed to reduced irrigation water allocations owing to prolonged drought [3]. This has consequently led to recurring drought episodes [5]. As such, the current drought in the Free State province has had devastating effects on the agriculture dependants, where the economy has been damaged beyond 50% in terms of employees and revenue losses [4], [10]. On that note, more than 80% of businesses have lost more than 50% of their employees owing to the drought that is taking a toll on the province [3], [13].

The Geographic Information System (GIS) and Remote Sensing techniques were combined with a Soil Water Assessment Tool (SWAT) hydrological model to estimate the impact of land use/land cover (LULC) changes on the catchment's water balance to evaluate these negative effects on water availability. By segmenting the catchment into sub-basins, the SWAT model can also simulate the effects of land management/administration practices, land-use change, and rainfall-runoff processes in detail [12]. Considering this, the hydrology of the C81F quaternary catchment in the Thabo Mofutsanyane District Municipality of the South African Free State Province was simulated using a SWAT model.

A continuous-time, semi-distributed, process-based river basin model is the SWAT (Soil and Water Assessment Tool) model. It was created to assess how different management choices would affect large river basins' nonpoint source pollution and water resources. Early in the 1990s, version 94.2 of SWAT, the first iteration, was released [14]. The model stands out from the competition because it can replicate the effects of LULC based on the Hydrological Response Unit (HRU) [10]. SWAT is a semi-distributed model that may run for extended periods and be used in both small and large catchments, according to [15]. Studies done by [11] assert that considering the foregoing, SWAT's benefit is in its capacity to apply complex soil water dynamics, which enables extremely extensive inputs concerning agricultural management. On the other hand, according to [16], the SWAT has many flaws, like the simulation of the groundwater element. As a result, when simulating lowland regions with reedy unsaturated zones and strong groundwater impacts on streamflow, the SWAT follows a lumped direct reservoir slant, which can lead to modelling errors [16].

Model calibration involves the estimation of model restrictions by relating experimental data for similar conditions with model outputs for a given set of presumed conditions[14]. Model validation is supported by and encouraged by the majority of these models [17]. Model validation, according to [14], is the process of running a model with input parameters that were measured or established during the calibration step. In light of the endorsed model evaluation statistics with conforming performance ratings and suitable graphical analyses [14], broad model validation principles have been acknowledged.

Based on this, the C81F quaternary catchment in the Eastern Free State is already facing a challenge of low rainfall and drought, resulting in water scarcity in the agricultural, municipal water supply, industrial, and environmental sectors [4]. A study conducted by [18] revealed that the Free State province experienced increased water challenges. On that note, as the water demand increased in the province, both quantity and quality were decreasing to critical levels. This study aims to evaluate the impacts of land use land cover (LULC) changes on the availability of water balance components for a period of 28 years (1990-2018).

2. Study Area

The study area is located in South Africa's Eastern Free State. It is governed by the municipality of the Thabo Mofutsanyane district. Figure 1 depicts the semi-arid region's dispersed habitation pattern over a catchment area of 67665.240 hectares (ha) and lies between latitude -27.945 and 28.783 longitude. The catchment experiences an average annual rainfall of 690 mm, with minimum temperatures in July of 1.0 ^{o}C and maximum temperatures in December of 26.5 ^{o}C. The Vaal and Orange River basins, which are also water management areas with similar climatic and hydrological characteristics, are where the catchment is located. The catchment has the highest proportion of soils with a clay-loam texture that is good for conservation.

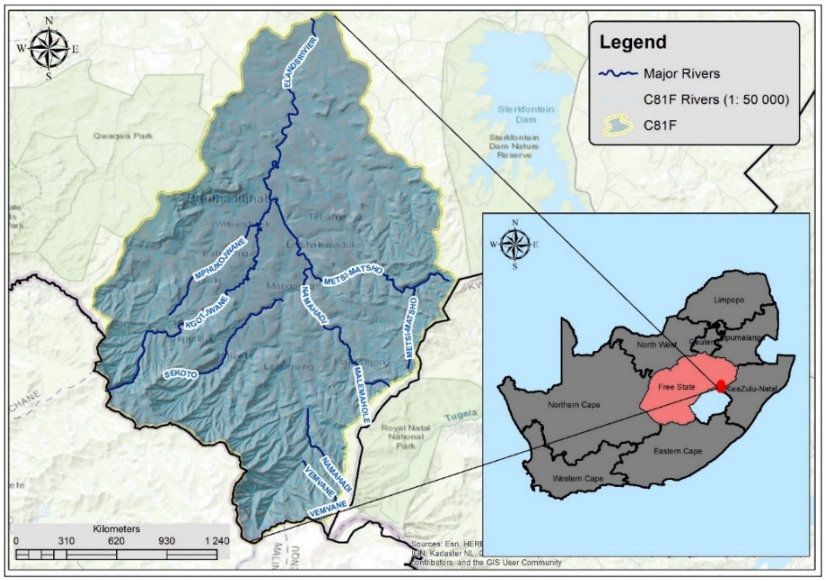

Figure 1: C81F quaternary catchment

There are two dams in the catchment area namely: metsimatsho and fika-patso. The rivers are quite a few malemahole, namahadi, elandsrivier, mphukojwane, kgotjwane, and sekoto. The major LULC classes in the catchment are agricultural land generics, barren land, and residential areas according to the SWAT model. The main crops in the study area are cherry, maize, wheat, and dry beans. Agricultural land generic has always been significant in the district municipality. One of the important areas where the textile industry flourished in the past was Thabo Mofutsanyana. The area still has a tremendous number of skills that can be used to boost the textile industry. The study area is a water-scarce region and this needs to be managed [19].

3. Methods and Materials

SWAT model inputs are shown in Table 2. The Digital Elevation Model (DEM) is important data, since all the topographic attributes of the catchment, and sub-catchment up to the HRUs level are derived from this dataset. The data set was sourced from earth explorer. The DEM was produced using four DEM tiles from earth explorer. ArcGIS was used to produce a 30m X 30m pixel-aligned resolution DEM which was formulated to describe the study area. The DEM shows different elevations within the catchment. The LULC map was produced using the SANLC database of satellite imagery, both the 1990 and 2018 LULC maps were used. The observed climate data was prepared according to ArcSWAT preference. Soil data has major influences on catchment hydrology; the different soil classes were defined based on the land type survey database collected from FAO-UNESCO global soil database. The climate data required included monthly precipitation (mm), minimum and maximum temperature (°C), relative humidity (%), solar energy, and wind speed (km/h). This climate data was collected from the South African Weather Service. The input data were collected and prepared to suit the SWAT model.

Table 2: Data Inputs for SWAT model.

Input Data	**Source**	**Resolution**
Digital Elevation Model (DEM)	Earth Explorer	30m x 30m
Land use land cover (LULC)	South African National Land Cover (SANLC)	30m x 30m

Soil data	FAO-UNESCO global soil map	5 km
Weather data	South African Weather Services (SAWS)	Daily timestep

The initial stage of SWAT modelling is watershed delineation. ArcSWAT uses the DEM to define hydrological features like reservoirs, ponds, and the direction of flow of streams. The watershed features, such as channel length, slope, slope length, channel depth, channel slope, and channel width, are necessary for the modelling process during the watershed delineation phase, which is the first stage in defining the area. The three steps will be followed to finally run the model.

Watershed delineation into sub-basins, with DEM as the primary input data, is the first stage of ArcSWAT. By manually incorporating an outlet into the stream flow network, the catchment data was altered. To compare predicted and actual stream flow data, it is advantageous to add an outlet to a stream flow measuring station at a known location. For the new outlet, stream flow data from 1990 to 2018 were accessible. Catchment delineation required calculation of sub-basin characteristics. The LULC map, soil information, and slope definition were used during the second stage, which was HRU definition. The SWAT modelling technique divided the delineated basin into numerous sub-basins that are connected by surface flow. The sub-basins are ranked in order of size. Then, each sub-basin is further divided into groups of homogeneous land cover/use, soil types, slope, and management practice, known as Hydrologic Response Units (HRUs) because they are anticipated to provide similar hydrological responses [20].

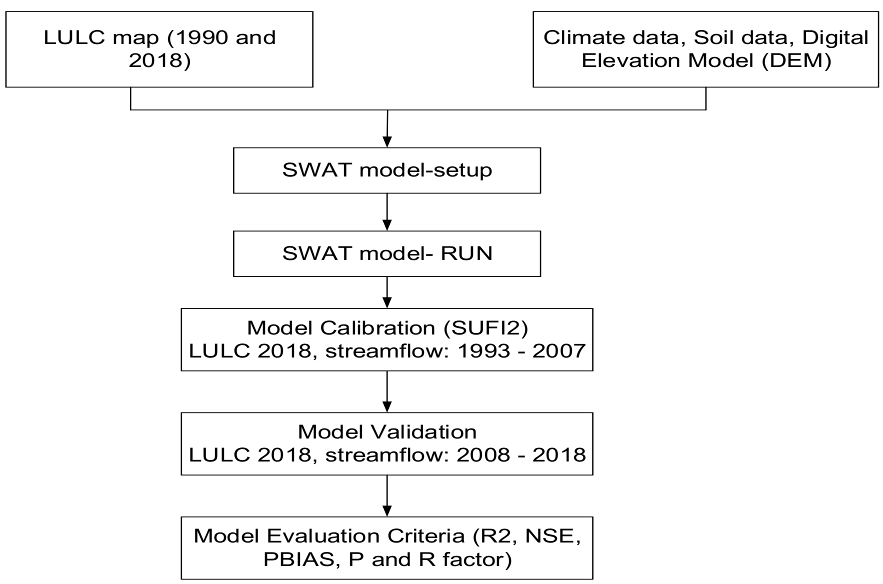

Figure 2: The flow diagram for hydrological modelling using SWAT model.

The application of the default input and weather data definition was done in the third stage, and the used meteorological data also includes the daily climate variables of precipitation, temperature, relative humidity, wind speed, and solar energy. ArcSWAT also includes a weather generator tool that aids in completing the data gaps from the simulation periods. This program can generate solar energy, relative humidity, and wind speed if we provide it with long-term daily precipitation rates in addition to the lowest and highest temperatures [21]. Before running ArcSWAT, this entails setting up the necessary specification period and PET calculation method. A three-year warm-up period was built into the model's design. Data for the years 1990 to 2018 were calibrated and validated using SWAT-CUP. LULC served as the foundation. The rainfall-runoff process was estimated using the curve number (CN method). Additionally, channel water routing was modelled using

Variable Storage Routing (VSR), and potential evapotranspiration was estimated using the Penman-Monteith equation. Once all three steps had been completed, the SWAT simulation was finished. The simulation was preceded by a three-year warm-up period. The simulation was run from 1990 to 2018 (including the warm-up periods).

4. Results

The LULC classes, coverage area in hectares, percentage, and rate of change over 29 years are displayed in Table 1.1. Over time, in the catchment area for 1990 and 2018, the LULC classes were reduced into seven classes based on the SWAT model. To find changes in the LULC classes of water, mixed wetlands, mixed forest, pasture, agricultural land generic, barren, and residential, the post-classification method is used. Table 1.1 shows how change detection in LULC using categorized data is done. A decline in LULC class is indicated by the negative rate of change.

The relative changes in land use in the research area between 1990 and 2018 have shown several odd patterns. Three classes (forest mixed, wetlands mixed, and pasture) have all experienced negative changes because of these changes. There has been a decrease of 2280.32 ha with a negative change (61.27%) in mixed forest compared to pasture. Wetlands, which have decreased by 338.33 ha over the past 28 years, represent the second adverse change (31.06%). Between 1990 and 2018, the overall degradation in pasture, which covered a region, decreased by 4303.50 ha, representing a negative change (8.90%). These accounted for the majority of the LULC class decline. An increase in LULC changes is implied by a positive rate of change. Over 29 years, the total area of uncultivated and agricultural land increased by 2456.27 and 3024.62 ha, respectively.

Table 1.1: Coverage of different LULC classes in the study area.

Class Name	**SWAT**	**1990**		**2018**	
		Area (ha)	**Area (%)**	**Area (ha)**	**Area (%)**
Water	WATR	162.4	0.24	189.46	0.28
Wetlands mixed	WETL	1089.41	1.61	751.08	1.11
Forest mixed	FRST	3721.58	5.5	1441.26	2.13
Pasture	PAST	48339.88	71.44	44036.38	65.08
Agricultural land generics	AGRL	2361.51	3.49	5386.13	7.96
Barren	BARR	669.88	0.99	3126.27	4.62
Residential	URBN	11320.35	16.73	12734.55	18.82

The integration of land use, soil, and slope classes led to the definition of the hydrologic response units. Threshold percentages of 25% for land use/cover, 10% for slope, and 10% for soil were set to lower the number of HRUS. The amount of clay loam has a significant effect on the chemical and biological processes of the soil because of its strong influence on the flow of water, air, and nutrients in the soil [22]. It is well known that a variety of soil physical characteristics, such as aggregation, bulk density, moisture content, total porosity, Zetterberg limits, and dispersion clay, influence soil organic carbon [23]. Due to the catchment's highest increase in cultivated agriculture, clay-loam is a great soil property texture that is very good for cultivated agriculture [24] . In a nutshell, the soil in the catchment is suitable for farming. With a coverage of 76.71%, clay loam is the soil type with the highest density (Table 1.2).

Table 1.2: Soil coverage and properties

SWAT Class	**Properties**	**ha**	**%**
Ws13-2ab-985	Loam	15677.98	23.17
Fr20-3bc-575	Clay	81.20	0.12
I-Bc-L-2-640	Clay-loam	51905.82	76.71

The total drainage area of the research area is 67665.24 hectares. The catchment was divided into 92 sub-basins and 25 sub-basins. The LULC classes were divided further into 92 HRUs and 25 sub-basins. Ten subbasins have 100% pasture coverage. In 1990, this LULC class dominated but gradually lost ground because of various factors in the research area. Due to the district's scenic location and rich cultural heritage, which forces the area to be covered in greenery and lovely grass, tourism is the area's secondary economic driver. The effects of mining, farming, and urban growth, however, have resulted in a decline in biodiversity in the province [4]. As a result of the anticipated climate changes, the catchment is expected to see an increase in the prevalence of alien plant species, an increase in atmospheric carbon dioxide levels, and a decrease in the frequency of frost [3]. As a result, trees will grow more quickly, and the already threatened grassland habitat will be invaded by the savanna biome [19].

Table 1.3: Sub-basins with 100% of pasture as a LULC class.

Sub-basin Number	**HRU number**
2	3
5	13-14
6	15-16
8	23-24
9	25-26
16	49-53
21	72-74
23	81-84
24	85-88
25	89-92

Table 1.4 lists the water balance analysis's average annual evapotranspiration (ET), surface runoff, lateral flow, and percolation simulations made using the 1990 and 2018 LULC maps. The overall effect of the LULC change on hydrology is assessed using the LULC maps from 1990 and 2018.

Table 1.4: Average annual water balance components for C81F quaternary catchment.

Water Balance Components	**1990**	**2018**	**Change**
Evapotranspiration (mm)	484.2	483.5	-0.7
Surface runoff (mm)	122.8	127.04	4.24
Lateral flow (mm)	39.61	39.48	-0.13
Percolation (mm)	135.49	132.1	-3.39

5. Discussion

The LULC adjustments in the catchment for the years 1990 to 2018 were calculated in this section. It is therefore confirmed, based on the LULC change analysis, that the water surface area has grown from 0.24 to 0.28% between 1990 and 2018. The metsimatsho and fika-patso dams are the only two recognized dams in the Thabo Mofutsanyane District Municipality.

In the period under review, there has been an increase in agricultural land overall, from 3.49 to 7.96%. The growth may be attributed to the expansion of the agricultural industry to increase productivity for the catchment and the nation's food security. To improve food security, the government stepped up its campaign to encourage localities to increase agricultural productivity. Additionally, the agricultural industry employs more people than any other industry. 90% of the nation's cherry crops are produced in the Thabo Mofutsanyana District Municipality.

Climate variability directly affects the amount of water in rivers, estuaries, dams, and lakes, among other bodies of water, through precipitation, evaporation, and surface runoff. Both human lifestyle and natural biological systems may be impacted by the distribution and modification of water resources in space. The effects of climate variability may be amplified by changes to the water resource systems, which may also affect the local vegetation [25]. All things considered, numerous water-related investments can be made to improve the availability, quality, and efficiency of usage [5]. More water will be required for domestic and industrial purposes as the world's population rises, forcing many water-scarce regions to import more food or produce more food with less water [12]. As a result, more and more farmers who also raise cattle are realizing that they are primarily grass farmers and secondarily raise livestock.

The truth is that the availability of grazing determines whether or not their farms are successful. Two types of False Karoo make up the remaining 22% of the Free State province in central South Africa, which is composed entirely of grassland for about 67% of the area [3]. Over time, this has led to a decrease in pasture. Farmers turned to pasture cultivation, which is frequently planted on marginal land that has previously been tilled. The residential area was 100% experienced in Sub-basin 11 and HRU 29. This demonstrates the increased growth and development taking place in the area. The district's population increased from 736 812 in 2018 to 739 305 in 2019, claims [3]. Additionally, the district has been growing at a 0.5% annual rate, which is lower than the provincial and federal rates of 0.6% and 1.5%, respectively. The need for residential sites brought on by population growth is one factor influencing change in this regard. Urbanization was found to add complexity to the hydrological reactions [12]. On the other hand, the negative effects of urbanization cannot be avoided. This includes environmental deterioration and pollution [3], [26]. According to [12], the dynamics of population growth are causing the urban area to grow, and the natural environment is not spared in the process.

The increase of surface runoff results from the expansion of residential areas, where roads, rooftops, and pavements obstruct water infiltration, while urban drainage systems expeditiously transport water away from the land, thereby exacerbating runoff. Furthermore, the decrease in pasture has led to an escalation in surface runoff, as the removal of trees diminishes the land's capacity to absorb and retain rainwater. The compaction of soil from agricultural practices has led to an increase in surface runoff by reducing the infiltration rate. The diminished groundwater recharge rates are influenced by the expansion of residential areas, which restricts water infiltration into deeper soil strata, while the reduction of pasture diminishes root systems that facilitate the movement of water to greater depths. The diminished subterranean water flow to streams and rivers adversely impacts baseflow during arid periods, attributable to the expansion of residential areas, which decreases soil porosity and permeability, thereby impeding water movement through the soil. Additionally, impervious surfaces obstruct water infiltration, hindering lateral movement within the soil. The decline in evapotranspiration results from the diminished area of pasture and forest, which limits water vapour release via transpiration. Additionally, reduced soil moisture for evaporation is attributed to heightened runoff and decreased infiltration. This study identifies that LULC changes result in heightened surface runoff due to impervious surfaces, deforestation, and drainage, leading to increased flood risk and soil erosion. The reduction in evapotranspiration, lateral flow, and percolation impacts modified climate, diminished cooling, decreased baseflow in rivers and streams, and lower groundwater recharge. The availability of data, particularly weather data, was one of the study's limitations. The dataset contained significant gaps and substandard quality, which can diminish model accuracy. The data preparation process was time-consuming.

The present research evaluated the effects of various scenarios for changing LULC on the elements of the water balance that are crucial for making decisions. The findings of this study suggest that SWAT can be a useful tool for predicting how changes in LULC affect C81F quaternary catchments' water balance at a reasonable cost, and the catchment's water balance was severely impacted by the observed changes in LULC. The combination of circumstances that could exist in the future and the actual response of the catchment to these combinations of scenarios are both uncertain, as are future LULC and climate. However, such scenario analysis in modelling enables comprehension of the likely effects of land use or climate change at a catchment scale.

5. Conclusion

It is well known that South Africa has a limited water supply and is under water stress due to the unpredictable rainfall patterns brought on by climate change and variability. After all of this, the water demand is still very high and exceeds the supply. Due to the destruction of river catchments, an increase in unchecked pollution activity brought on by the destruction of wetlands, damming of rivers, deforestation, and rising urbanization, freshwater is becoming scarcer and of lower quality in South Africa. This study aimed to assess how LULC changes affected the water resources in the C81F quaternary catchment. In this regard, computer-based hydrologic simulation models like the SWAT model, GIS, and remote sensing were used.

The C81F quaternary catchment was divided using the DEM into 25 distinct sub-basins based on reaches (streams), which were then divided into 92 HRUs. The total area of the designated catchment is 67665.24 ha.

The water resources of the catchment are impacted by changes in LULC. One of the inputs to the SWAT model is LULC maps. The change detection evaluation describes and measures the difference between the LULC maps of the same scene at various times. The classified LULC maps of the two distinct periods are used to estimate the distribution of different land cover types and to spot changes that occur within the data range. In 1990, pasture dominated the LULC, followed by residential development and forest mixed development, which together accounted for 71.44, 16.73, and 5.50% of the total area. Water and barren land were the least dominant classes. More research on this catchment is advised to evaluate the potential effects of other elements of the water balance, such as evapotranspiration, a potential rise in abstraction, groundwater, and climate change, on the runoff. It is necessary to analyse the region's water resources and future hydrology. A thorough soil map of the study area must be created before applying the model to predict erosion, for instance, to apply the model to erosion.

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