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REVIEW

Remote sensing of land use-land cover change and climate variability on hydrological processes in Sub-Saharan Africa: key scientific strides and challenges

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ABSTRACT

The impact of land use land cover (LULC) change and climate variability on water resources poses as a major threat in semi-arid environments, especially in the sub-Saharan Africa. Countries in sub-Saharan Africa are vulnerable to water scarcity. Hence, there is an urgent need for understanding the various methods for LULC change and climate variability assessment, to aid in water resources management at various scales. Various studies have modelled and assessed the effect of LULC change and climate variability on hydrological responses, using different approaches. In this regard, this paper provides a detailed review on the progress of various remote sensing techniques in modelling and assessing the effect of LULC change and climate variability on hydrological processes. The review also highlights the critical scientific strides and challenges of remotely-sensed applications in LULC change characterization and total evaporation estimation. Specifically, research gaps in the estimation of total evaporation in response to LULC change and climate variability, using remote sensing are also highlighted. The study demonstrated remotely-sensed methods used in hydrologic models such as the SCS-CN, WetSpa, JULES and the SWAT model that are used to determine run-off and streamflow. These methods have a component of total evaporation however evapotranspiration (ET) is not the sole focus. The study showed that the application of the remotely sensed SEBS tool has been widely accepted as a viable method to estimate total evaporation. However, it has been observed that there is limited focus on the impact of LULC change and climate variability on total evaporation.

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Climate variability; hydrological response; land cover dynamics; remote sensing; total evaporation; sub-Saharan Africa

1. Introduction

Water is an essential natural resource for all forms of life, with great socio-economic and environmental value (Dwarakish and Ganasri 2015; Abose and Begeno 2020). For example, more than half of the 144 million people relying on water directly from rivers, lakes and ponds live in the Sub-Saharan Africa. However, water availability remains one

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of the major current and future challenges facing Africa. About 25% of the current African population experiences water stress (Al-Gamal 2020). In addition, according to the WHO/UNICEF (2019) progress report, in 2017, 9/10 of the 785 million people who still use limited services, unimproved sources or surface water live in three regions: sub-Saharan Africa (400 million), Eastern and South-Eastern Asia (161 million), and Central and South Asia (145 million). Some areas of the sub-Saharan Africa are seriously under threat due to the deterioration of water resources in terms of quality and quantity, rapid population growth (Mukherjee et al. 2018; Munoth and Goyal 2020) and inappropriate land management practices (Dibaba et al. 2020) as well as global climate change (Dey and Mishra 2017). Therefore, changes in the hydrology and water resources, due to climate and land modification, warrant intensive attention for appropriate planning and management to achieve its sustainable utilization.

Climate and land use land cover (LULC) change have adverse implications on the natural hydrologic system in terms of variation in the surface runoff, stream flow, evapotranspiration (ET), precipitation, infiltration, groundwater recharge and water quality (Dwarakish and Ganasri 2015; Mahmoud and Alazba 2015; Aduah et al. 2017). However, areas experiencing LULC change can have a positive affect on the hydrology of the area as a result of increasing afforestation (Dittrich et al. 2019). According to Woyessa and Welderufae (2021), increasing forest cover could result in a reduction of annual flow by up to 15% and annual surface runoff by up to 30%. This can lead to a corresponding reduction of the magnitude of peak fow during floods as well as peak flows. However, this is only applicable to mature forest cover which can take several years to develop. Urbanisation has contributed to major changes in LULC and climatic conditions resulting in increased land surface temperature and urban heat islands (Mathew et al. 2016; Berihun et al. 2019). Globally, various studies have focused on the importance of run-off and streamflow whereas with a few tackling the impacts of LULC and climate variability on ET. For example, Garg et al. (2019) observed that the annual run-off had increased by approximately 45% between 1985 and 2005, due to an increase in built up area and subsequent declination in forest areas and croplands. Mango et al. (2011) observed increases in precipitation and temperature resulting in noticeable run-off response in Kenya. These changes have therefore influenced hydrological processes across various scales. Shoko et al. (2015) states that ET is the second largest water balance component, which plays a vital role in hydrological processes, after precipitation, and according to Jin et al. (2013) the surface ET on a regional scale can substantially influence the amount and spatial distribution of water resources. Evapotranspiration describes the loss of water from the Earth’s surface to the atmosphere by the combined processes of evaporation from the open water bodies, bare soil and plant surfaces and transpiration from vegetation (Li et al. 2009). It is one of the major consumptive uses of irrigation water in agriculture therefore allowing it to be a suitable variable in understanding the impact of LULC and climate variability on water resources in the sub-Saharan Africa, considering its aridity nature. As ET varies with land surface and local meteorological conditions, it is difficult to be quantified. However, the use of surface energy balance algorithms, based on remotely sensed data, have shown to be quite promising for the estimation of ET on both local and regional scales (Ferreira et al. 2016). Therefore, assessing the impact of LULC and climate variability on hydrological parameters, specifically ET, contributes to our understanding of the effect of these two variables on water resources in all regions and in particular regions where water scarcity is a great concern, such as sub-Saharan Africa. This will further aid appropriate planning, monitoring and management practices which have already started being implemented in sub-Saharan Africa, such as the improvement

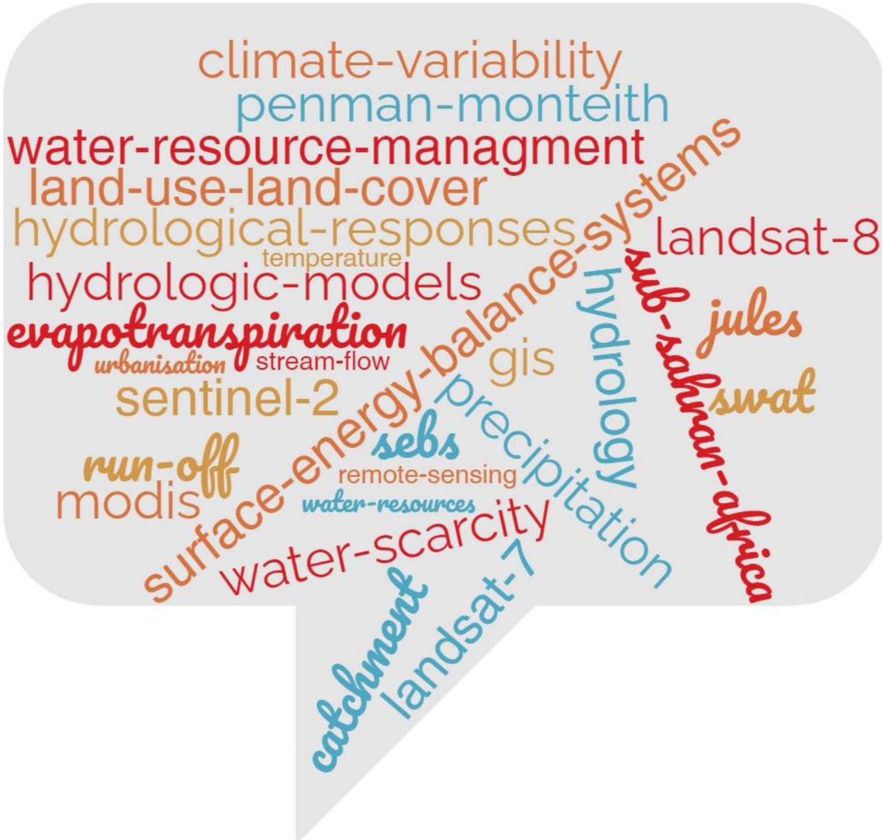

Figure 1. Showing the relevant words used during the literature search.

of germplasm in maize crops that have a tolerance to drought and heat stress (Cairns et al. 2013). Countries with limited resources will benefit with further understanding of LULC change and climate variability. Thus the aim of this review is to provide a comprehensive and detailed overview on the progress of scientific research in assessing the impacts of LULC and climate variability on hydrological responses with the use of remote sensing applications.

1.1. Literature search

The search for available literature on the effects of LULC change and climate variability on hydrological responses using remote sensing in sub-Saharan Africa was carried out using Google Scholar as the main search engine as well as from the use of scientific journals. Different library data bases such as Web of Science and Science Direct are linked to Google Scholar which were also accessed during the literature search. The search criteria was used to find scientific studies that were published between the years 2000 and 2021 in sub-Saharan Africa. The search included a range of key words such as "water resources", "LULC", "climate variability", "hydrological responses", "evapotranspiration", "remote sensing", "Sub-Saharan Africa" and more as depicted in Figure 1.

Literature was then separated into three categories for the above mentioned years as (i) the effect of land use land cover change on hydrological responses using remote sensing,

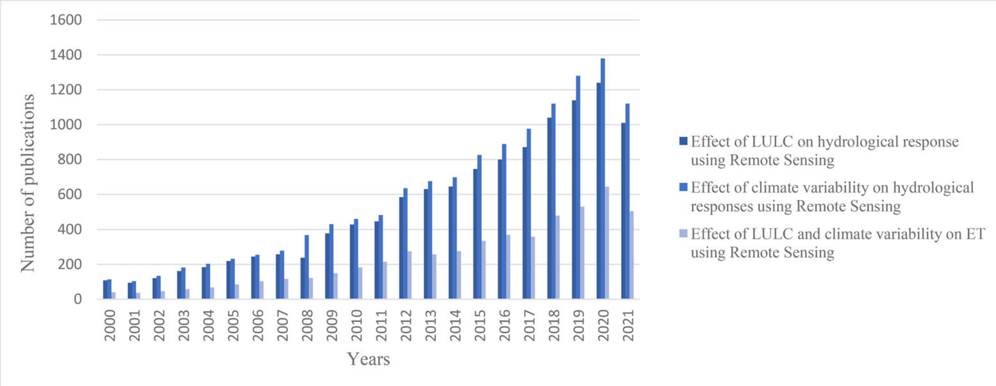

Figure 2. Number of published journal articles in sub-Saharan Africa relating to the effects of LULC on hydrological responses, effect of climate variability on hydrological responses and the effect of LULC and climate variability on ET using remote sensing.

(ii) the effect of climate variability on hydrological responses using remote sensing and (iii) the effect of land use land cover change and climate variability on evapotranspiration using remote sensing (Figure 2) After screening and selecting literature based on the above categories, 221 published scientific articles and 2 conference papers were narrowed down.

The results showed a vast number of studies overlaps can be observed between categories (i) and (ii) as numerous studies focussed on land use land cover and climate variability effect on hydrological responses. Majority of this work (approximately 15 600 publications) was conducted between 2000 and 2021, with Further observation indicates that the gradual increase in ET monitoring using remote sensing suggests that further scientific investigation is needed in sub-Saharan Africa.

2. Impacts of land use and land management on hydrological processes

Land use and management influence different hydrological processes. For example, areas characterised by bare surfaces or pavements typically experience more runoff when compared to vegetated areas (McGrane 2016). In this regard, land cover characteristics are a key determinant of the hydrological processes. Further, LULC change is a major challenge facing the global environment with rapid population growth being one of the leading drivers of LULC as it leads to urbanization, increase in cultivated land and residential area (Berihun et al. 2019, Wagner et al. 2016). At least 30–50% of global land cover has been affected by land use change, primarily for agricultural purposes to increase food production for the increasing human population (Odongo et al. 2019). Recent developments in sub-Saharan Africa show an increasing trend of conversion of natural land cover into arable land (Näschen et al. 2019). According to Bruinsma (2003), the sub-Saharan Africa is expected to experience further large scale land use change for food production in the coming years. LULC changes occur on all continents, but these changes are more pronounced in African tropical mountainous areas including Burundi, Ethopia, Kenya, Malawi, Mozambique, Uganda, Rwanda, Tanzania and Zambia (Desta and Fetene 2020). In these countries, socio-economic development, population increase and human pressures on agricultural lands have become the main drivers of LULC changes. For example, a study conducted by Chemura et al. (2020), in Zimbabwe, showed a significant human modification on part of the Buzi Headwaters, with cropland, plantation forest, coffee, tea and water now dominating the landscape of the sub basin. In addition, from 1990 to 2015 the decline of natural forest cover in countries like Kenya, Tanzania and Zambia occurred at an annual rate of 1 to 2% (Guzha et al. 2018). As a result such land use conversions have led to the modifications of some of the key hydrological components, especially interception rates, soil water, ET, infiltration, water quality and groundwater thus, leading to changes in surface runoff, streamflow and flood frequency (Paul 2016).

Numerous studies focusing on the impact of land use conversions on hydrological responses have been conducted in the sub-Saharan Africa from as early as 2000 to present (Table 1). However it can be noted that majority of studies have focused particularly on the impact of stream flow and surface run-off. However, beyond Africa, only a few of the studies conducted, assessed the impact of LULC change on run-off (Garg et al. 2019; Wang et al. 2017). These studies have revealed that in certain time periods of their studies, there were significant increases in run-off due to the land conversion from natural vegetation or bareland to urbanised or built up areas. For example, Garg et al. (2019) observed that the annual run-off had increased by approximately 45% from the year 1985 to 2005 due to an increase in built up area and subsequent declination in forest area and crop land. Similarly, in 2017, the Nile Basin experienced an increase in run-off due to the removal of woodland coverage (Woldesenbet et al. 2017). To determine the impact of LULC change on streamflow, studies conducted by Xu et al. (2019), Candela et al. (2016), Paul (2016) and Shao et al. (2018) have revealed that there have been a decrease in streamflow as a result of LULC change. According to a study conducted in China by Shao et al. (2018), during the period 2001–2014, LULC change induced a 1.94% decrease in the mean annual streamflow. However, Welde and Gebremariam (2017) noted an increase in streamflow by 6.02% in Northen Ethiopia, and this was similar to the findings in Ghana. As of recent years, there has been an increase in the number of studies being conducted on the impact of LULC change on hydrological responses in Sub-Saharan Africa with particular focus on ET.

Studies conducted in Africa have analysed the impact of LULC on ET (Billi and Caparrini 2006; Hegazy and Kaloop 2015; Cheruto et al. 2016; Welde and Gebremariam 2017; Moses and Hambira 2018; Berihun et al. 2019; Odongo et al. 2019; Chemura et al. 2020). These studies concluded that changes in LULC, crop rotation and crop types mainly influence ET in a watershed. In addition, forest areas promote elevated ET because of low albedo, deep roots and water interception. According to Berihun et al. (2019) the estimated ET increased between the years 1981 and 2017 under changing land cover in Ethiopia. Similarily, Awotwi et al. (2019) observed a 13.25% increase in ET from 1986 to 2016 due to an increase in cropland, settlement and mining at the detriment of forest areas in Ghana. On the other hand, some researchers are of the notion that LULC change had a greater impact on the hydrological cycle than climate change (e.g., Xu et al. 2019).

3. Impacts of climate variability on hydrological processes

Climate variability has enormous influences on the environment and social development on which a growing human population relies. Understanding climatic patterns is of great significance when many global challenges such as food insecurity, water crisis, biodiversity loss, and health issues rely on changing climate (Xu et al. 2017). Urbanization is one of the main factors causing unnatural changes in climate patterns around the globe (Mathew et al. 2016). One of the major implications of urbanization is the increase of surface temperature and the development of Urban Heat Island (UHI). For example, a study conducted in Ghana describes the UHI phenomenon as a result from the relative rise of land

Table 1. Main findings based on the effect of land use land cover on hydrological responses in sub-Saharan Africa.

Region	Country	Main findings	Strengths	Challenges	Reference & citations
West Africa	Burkino Faso	Natural vegetation reduced whilst cultivated areas and bare soil drastically increased resulting in changes in hydrological responses characterised by increases on the average run-off and daily discharges.	The impact of land use change on soil was tested through monthly river flow modelling and showed a marked improvement in flow simulation using the time-varying values of soil.	Limitations in monthly river flow conceptual models and few measurements conducted over degraded land surfaces hindered the study.	Mahe et al. (2005) Citations: 265
Southern Africa	Tanzania	Changes in hydrology are attributed to the encroachment of agriculture which was found to have doubled. The results showed a sharp increase in flood peak flows by 7%.	This study produced baseline and derived thematic data on LULC, as well as rainfall and river flows, to enable assessment of their effects on the basin's hydrology.	Further studies are required to determine if the shift in rainfall peaks predicted in this study are associated with climate change.	Matti et al. (2008) Citations: 0
East Africa	Ethiopia	Changes in LULC decreased the water-storage capacity of soils with a corresponding increase in surface run-off. The observed changes in land degradation and surface run-off are highly linked to the change in land use land cover.	The SCS application could be used in areas where hydrological data are limited as the SCS model is a good substitute to reliably predict surface runoff in areas with poor vegetation cover.	Lack of a land slope factor in the SCS model hinders the study of soil storage capacity.	Gebresamuel et al. (2010) Citations: 101
West Africa	Nigeria	The model results show increases in the run-off coefficient with decreases in forest cover.	Three models were found suitable for simulating rainfall run-off to aid the understanding of the impact of LULC and climate change in assessing basin water stress.	Issues with limited rain gauges contributed to poor rainfall representation, thus affecting the model.	Ayeni et al. (2015) Citations: 12
West Africa	Kenya	Simulation results indicated an overall 3% stream flow increase for the whole watershed, which can be attributed to farm expansion and degradation of natural forest.	The research developed an integrated approach for combining hydrological modelling with remote sensing classification to assess the long-term impacts of LULC change on run-off.	During the classification process, errors that might have occurred during data processing contributed to changes in statistical values for land cover.	Edgar (2016) Citations: 0

(*continued*)

Table 1. Continued.

Region	Country	Main findings	Strengths	Challenges	Reference & citations
East Africa	Ethiopia	The expansion of cultivation land and the decline in woody shrubland has increased wet-season flow by increasing surface run-off, while decreasing dry-season flow by lowering the groundwater component.	The method used in this study showed that changes in LULC to hydrological parameters, provides information that will allow decision-makers to make prominent choices regarding land and water resource planning and management.	Limitation of the curve number method used in the SWAT model resulted in inconsistency in discharge, as it considers average daily rainfall depth instead of intensity and duration.	Woldesenbet et al. (2017) Citations: 144
East Africa	Rwanda	Results showed seasonal trends in water quality associated with high water flows and farming activities. Conductivity, temperature, dissolved oxygen, and pH decreased with increasing discharge.	This study contributed to a stronger understanding on how agricultural practices affect water quality which correlates to other hydrological components such as discharge.	Future field measurements should include more frequent simultaneous measurements of DO, pH, conductivity, and temperature to characterize the impacts of different agricultural practices.	Uwimana et al (2017) Citations: 16
Southern Africa	tanzania	The agricultural land and evergreen forests increased whilst forests decreased by 12%. Such LULC changes decreased the total water yield while increasing evapotranspiration and surface run-off.	SWAT model parameterization serve as a starting point in subsequent studies within watersheds which may apply SWAT as a tool for hydrological processes analysis.	The study highlighted that parameter values may need some minor customizations because catchments differ in their physical characteristics.	Hyandye et al. (2018) Citations: 14
East Africa	Ethiopia	The results of this study showed that run-off, streamflow and sediment yield showed increases due to LULC change.	This study contributes to identify the change sensitive subbasins within the watershed, so that the decision-makers can implement management strategies.	Due to the difference in the scale, spatial resolution, and season of map preparation, securing different land use maps were the major constraints of this study.	Assfaw (2020) Citations: 0
Southern Africa	Zimbabwe	Major conversions were from wetland cover to crop fields suggesting agricultural encroachment onto the wetland area. Wetland area, thus, significantly decreased by 6%	This study contributes towards quantifying wetland changes over time provides a scientific bases for wetland protection.	Study results confirm the need for parameter optimisation for accurate classification results.	Sibanda and Ahmed (2021) Citations: 7

surface temperature (LST) in the urban areas when compared to the surrounding rural environment (Athukorala and Murayama 2020). In addition, LST is increased by anthropogenic heat discharged by energy consumption, increasing land surface coverage by artificial materials and the decrease in vegetation and water pervious surfaces which can reduce LST through ET (Sundara Kumar et al. 2012). LST is one of the primary key parameters controlling the physical, chemical and biological processes of the Earth and is an important factor for study of urban climate (Mathew et al. 2016). Furthermore, the UHI phenomenon is becoming prominent in megacities and the hinterlands of Africa, especially in tropical and subtropical climatic regions (Athukorala and Murayama 2020).

Globally there has been severe impacts on hydrology which scientists attribute to climate change resulting in dwindling water resources (Kotir 2011; Nkhonjera 2017). In addition, sub-Saharan Africa is a dry and water scarce continent where roughly 300 million people suffer from water shortages, with 80% of the land being desert coupled with arid and semi-arid climatic conditions (Gizaw and Gan 2017). Furthermore, some water resource impacts will occur through changes in the frequency and severity of extreme events in the form of droughts and floods (Nkhonjera 2017). For example, according to the Intergovernmental Panel on Climate Change (IPCC 2014) near surface temperatures have increased by 0.5 °C or more during the last 50 to 100 years over most parts of Africa and these temperatures are projected to rise faster than the global average increase during the 21st century over southern Africa. It is further observed by Serdeczny et al. (2017) and Gizaw and Gan (2017) that these enhanced heat wave probabilities are associated with deficient rainfall conditions that tend to occur during El Niño events, a weather phenomenon that is very common in Southern Africa. In addition, sea surface temperature (SST) is another factor to take into consideration when discussing climate variability. SST has important local and remote influence on globalclimate through the distribution and transport of heat and moisture, which in turn affect precipitation and air temperature patterns across the globe (Ruela et al. 2020). According to Urama and Ozor (2010) the observed effects of climate variability impact water resourses increased flooding, droughts, change in the frequency and distribution of rainfall, drying-up of rivers, melting of glaciers, receding of water bodies, landslides, and cyclones among others. For example, most parts of the sub-Saharan Africa are vulnerable to flooding, with the East, South and Central regions having the most prevalent flood disaster, followed by West Africa. In addition, floods across the sub-Saharan Africa are reported to be the worst in decades in some places such as in Burkina Faso, Chad, Ethiopia, Ghana, Kenya, Liberia, Mali, Niger, Nigeria, Senegal, Sudan, Togo, Uganda, and Rwanda (Ngoran et al. 2015).

Another pressing result of climate variability to which is a particular concern for sub-Saharan Africa is the increase in drought occurrence. Since the late 1960s, droughts have caused much suffering in Africa. Severe droughts were experienced in 1973 and 1984 when almost all African countries suffered reduced rainfall, which particularly affected several million people in the Horn of Africa, the Sahel and Southern Africa (Ngoran et al. 2015). For example, between June 2015 and June 2018, South Africa experienced the worst drought since 1904 with the City of Cape Town, Western Cape being the hardest hit (Ziervogel 2019). According to Ziervogel (2019) rainfall recorded over the three year period 50 to 70% of the long-term average and 2017 recorded the lowest rainfall record since the 1880s. Futhermore, the low rainfall along with low run-off translated into falling dam levels and affected six of the largest dams with dam levels dropping from 100% in 2014 to 71%, 60% and 38% in 2015, 2016 and 2017. Droughts are endemic in both Southern Africa and the Sahel region of western and northern Africa and climate change

Table 2. Main findings, strengths and weaknesses based on the impacts of climate variability on hydrological responses in sub-Saharan Africa.

Region	Country	Main Findings	Strengths	Weaknesses	Reference
East Africa	Kenya	Increases in precipitation and temperature result in noticeable run-off response. However, there is little impact on annual water yields or mean discharge.	The SWAT model was successfully used in a poorly gauged rural African catchment due to new satellite-based rainfall estimates, minimal additional input data, and proper attention to manual or automatic calibration of the model.	Catchment scale runoff model calibration is challenging and is impeded by uncertainties like processes unknown to the modeler. The challenge is even greater in data scarce regions of Africa.	Mango et al. (2011)
Southern Africa	Zimbabwe	The results showed that there was an increase in mean annual temperature thus resulting in a decline in the size of surface water resources.	The study contributed to understanding the trend of decreasing water resources in Mazowe Dam Catchment is expected to continue due to temperature increases and reductions in precipitation.	Climate change prediction in Mazowe Dam Catchment is severely limited by a lack of complete historical data on temperature, precipitation evaporation and evapotranspiration.	Kaseke et al. (2012)
West Africa	Benin	This study showed that warmer temperatures will severely limit crop production as the impact of climate change will severely affect the potential for increasing rainfed cropping.	The study highlights using an integrated approach to assess where climate change can be expected to have multiple and major implications on cropping systems and water regulations.	Due to the high uncertainties in precipitation projections in West Africa, a larger ensemble of climate projections is required to estimate the impacts of climate change on water resources accurately.	Duku et al. (2018)
Southern Africa	Tanzania	The warmer climate will increase evapotranspiration and decrease water yield by approximately 35 and 8%, respectively.	The satisfactory model calibration and validation results are interpreted as the outcomes of good model input data, notably rainfall and model parameterization.	Lack of observed temperature data.	Hyandye et al. (2018)

(*continued*)

Table 2. Continued.

Region	Country	Main Findings	Strengths	Weaknesses	Reference
East Africa	Ethiopia	The contribution of climate change is larger than the land surface changes on water resources in this study as the results indicated that 70% of the changes in water resources is attributed to climate change.	The study revealed and re-affirmed that water availability is negatively affected by climate change in the eastern and northern part of Ethiopia.	The deviation and elasticity indexes resulted in limitations in the study.	Abera et al. (2019)
West and Central Africa	Sahel	The results show rising temperature, suggesting an increase in potential evapotranspiration. Overall, across the region, a significant increase in discharge is expected by the mid-21st century	Using multiple climate-based models proved to be successful in predicting the effect of climate variability on hydrological components in present and future scenarios for Africa.	Uncertainties in model simulations resulted in variable statistical results.	Sidibe et al. (2020)
Southern Africa	South Africa	Due to climate change, the occurrence of drought is likely to increase, which means the impacts of droughts based on historical, present, and future scenarios need to be analysed, especially in Africa, which is a data-scarce continent.	This study shows that remote sensing technology has improved drought and water resource monitoring including climate variability.	Drought monitoring and water detection indices were developed for specific satellite data, therefore with the development of new satellites, new indices need to be developed and tested across diverse environments to enhance their utility	Bhaga et al. (2020)

is projected to increase the risk of drought over much of Africa in the 21st century hence the urgency to monitor the impact of climate variability on water resources.

The impacts of changes in climate (e.g., precipitation and temperature) cause variations in hydrological processes including surface runoff, timing and magnitude of streamflow, and flood events. The response of streamflow to changes in precipitation has been shown to be more sensitive than to changes in temperature and evapotranspiration, despite the fact that the latter two factors can also increase or decrease streamflow (Xu et al. 2019). Shao et al. (2018) stated that the increased temperature could result in corresponding changes in the timing and volume of spring flood and ET as observed in China. In addition, the variability of precipitation, especially the changes in frequency and intensity of extreme precipitation events, could lead to a variation in stream flow and peak flow. Rainfall variability is generally high in Africa, particularly in the continent's drylands. Greater variability affects biophysical resources such as crops directly and social conditions indirectly (Buhaug et al. 2015). The crop production systems in Africa are predominantly rain-fed, implying high interannual volatilities in output. Although income loss from low production in dry years may be offset partly by higher yields in wet years, increasingly erratic weather patterns and associated increases in droughts, wildfires, and floods threaten to cause a breakdown in agro-ecological systems across the continent in the absence of new investments and successful adaptation

According to studies conducted in Africa (Table 2) regarding the effect of climate variability on hydrological processes, climate variability significantly influences the changes in runoff and ET (Legesse et al. 2003; Mercy 2017; Moses and Hambira 2018; Berihun et al. 2019; Odongo et al. 2019). A change in the patterns of climatic parameters due to climate change implies a change in ET rates over water resources. This could have significant impacts on water availability, quantity and quality, particularly in poor semi-arid regions such as those in sub-Saharan Africa (Moses and Hambira 2018). In a study conducted by Op de Hipt et al. (2019) in West Africa, states that climate change has a larger impact on discharge and sediment yield and showed results of an increase of 3.3% in ET due to climate variability. Besides, the role of LULC change is more dominant than that of climate variability in the annual surface runoff and ET responses as a result of LULC conversion and temperature variation across the watersheds during the study period. Studies show that climate variability proves to have a significant impact on run-off, ET and drought possibility in Sub-Saharan Africa. Accurate determination of regional ET and estimation of the evolution of the climate, water resources planning and management, agricultural water saving crop production simulation and environmental issues have important practical significance (Ma et al. 2014). Understanding climate change is vitally important as such changes coupled with climate variability have the potential to multiply existing threats to human security including water, food, health, and economic insecurity, all of which are of particular concern for Africa (Kotir 2011). It is anticipated that climate change will likely worsen marginalised communities' poverty levels due to the impacts of extreme weather events and costs associated with the damage caused by flooding.

4. Use of remote sensing to estimate hydrological responses

Thirteen thousand one hundred articles relating to the application of remote sensing to estimate hydrological responses were found whereas 17 200 articles were published on the impact of LULC change and climate variability using other various methods in sub-Saharan Africa. Surface run-off, sediment losses, streamflow and ET are important hydrologic responses from LULC change and climate variability occurring over the watershed

Table 3. Summary of studies conducted assessing various remotely sensed data within SEBS and highlighting the strengths and weaknesses.

Remote sensing data with resolution (m)	Results and observations	Strengths	Weaknesses	References
AATSR (1000 m) & MERIS (1000 m)	Simulated ET through the SEBS model and satellite imagery demonstrated very high correlation with the ground truth data in Egypt, Africa.	The Nile Delta region has relatively simple surface relief. Therefore, the application of the SEBS model proved to be beneficial in estimating ET.	Limiting conditions for the application of the SEBS model may rely mainly on surface roughness.	Elhag et al. (2011)
MODIS (1000 m) & Landsat 8 (30 m)	The Landsat 8 data sets proved to be more beneficial for accurate spatial representation of ET at catchment scale compared to that of MODIS data in South Africa.	This study highlighted that the SEBS model can be effectively used to estimate water loss within a catchment.	The use of fine resolution multispectral sensors, such as the RapidEye and WorldView-2 images may aid in quantifying ET levels in arid environments.	Shoko et al. (2015)
MODIS (1000)	The use of MODIS imagery to derive ET in SEBS does not adequately represent ET. The SEBS model was shown to consistently overestimate.	Satellite earth observation has shown potential in capturing spatially representative hydro-meteorological flux data and therefore represents a practical alternative for estimating ET.	The use of MODIS imagery to derive ET in SEBS does not adequately represent the inter-field spatial variability of energy fluxes. This proved to be a significant limitation to this study.	Gokool et al. (2016)
Landsat 5 & 7 (30 m)	Although SEBS showed accurate representation ET estimates, Landsat 5 & 7 imagery does not acquire data constantly and has a scan-line correction issue, respectively.	In this study it was shown that remote-sensing data can be used in ET estimation methods to much larger areas, even where measured meteorological data may be sparse.	Accurate estimates of the simulated soil heat flux, when compared to that measured, were not always achieved due to high variability and complexity of this parameter.	Jarmain et al. (2009)

(*continued*)

Table 3. Continued.

Remote sensing data with resolution (m)	Results and observations	Strengths	Weaknesses	References
MODIS (1000 m) & ECMWF (-12 500 m)	Certain land use conversions may dominate climatic influences and consequently alter water balance more than climate.	This study showed that the results of the impact of LULC and climate variability on ET provided valuable insights that will aid catchment managers.	The complexity of ET quantification may hinder accurate ET estimates.	Odongo et al. (2019)
Landsat 7 and 8 (30 m)	The SEBS ET estimates and the in-situ ET data are fairly accurate for the validation of the study.	Remote sensing proved to be a viable option to estimate ET over large areas.	A case of over-estimation of ET was present in some cases.	Ramjeawon (2016)
MODIS (1000 m)	SEBS proved to be a useful tool for the determination of spatial ET.	This study showed that SEBS has potential for estimating spatial actual evapotranspiration which can aid water resources management and planning.	Limitations to this study included roughness parameterisation, the spatial variability of input temperature data and heterogeneity.	Rwasoka et al. (2011)

systems hence accurate estimation is vital. However, some conventional methods of run-off estimation, for example, using Soil Conservation Service (SCS) model can be time consuming and error prone (Gajbhiye 2015). As a result of technological advancements, resource monitoring and the assessment of areas of interest, information derived through remote sensing has to be integrated in GIS (Thakur et al. 2017). Thus, the combination of remote sensing along with GIS application aid to collect, analyse and interpret the data rapidly on large scale periodically and is very much helpful for watershed monitoring and planning (Roy and Inamdar 2019). Therefore, remote sensing and GIS techniques are being increasingly used.

SCS model parameters have geographic characteristics however; recently researchers have incorporated the run-off curve number. The new SCS-CN model was applied in a study in Ethiopia (Gebru et al. 2019) where remotely sensed LULC maps were integrated with hydrological modeling to evaluate long-term hydrological consequences of LULC change. In particular, the conventional SCS-CN model was used by incorporating the variation in daily curve numbers, with respect to the variability of antecedent rainfall, potential evapotranspiration (PET), with integrated LULC change images, and grid-based hydrological soil texture classification groups (HSG). The modified SCS-CN-based models provide a hydrologically sound procedure for a more accurate representation of the catchment behavior through analysis of the hydrological response of LULC changes, as indicated by their impact on the PET and run-off co-effcient in northern Ethiopia (Gebru et al. 2019). The results showed promising outcomes with information needed for further monitoring of land use planning and water resource management.

Other studies in sub-Saharan Africa have assessed the use of the WetSpa hydrologocial model. WetSpa is a physically-based distributed hydrological model for predicting Water and Energy Transfer in Soil, Plants and Atmosphere on regional or basin scale, developed at Free University of Brussels, Belgium by Wang et al. (1996). It is a GIS-based distributed hydrological model capable of predicting outflow hydrographs at basin outlet or any converging point in a watershed with a variable time steps (Desta et al. 2019). The WetSpa model has been widely applied for stream flow modeling, land use impacts, and climate change impacts. Hence, the WetSpa model has been successfully applied in various ranges of studies under a wide variety of climate conditions. The main inputs of WetSpa are a digital elevation model (DEM), digital land use and soil maps, and time series of precipitation and evaporation. A study conducted by Desta et al. (2019) in Ethiopia, used daily precipitation and potential evapotranspiration (PET) data in predicting streamflow. The results showed that the WetSpa model simulates the runoff appreciably well for the study area.

Further, the Joint UK Land Environment Simulator (JULES) is also a widely used process-based land surface model that was developed at the UK Met Office (Clark et al. 2011) that incorporates remotely sensed data. JULES can be run uncoupled as a standalone tool to assess water resources and to study land–atmosphere interactions and impacts (Martínez-de la Torre et al. 2019). To determine run-off, the precipitated water that arrives at the surface after vegetation interception, JULES first determines the infiltration excess component of surface run-off from the soil hydraulic characteristics. Pinnington et al. (2018) assessed the application of JULES in Ghana and the study used the global land configuration 4.0 of JULES designed for use across weather and climate modelling timescales and systems. Furthermore, the use of the Tropical Applications of Meteorology using Satellite (TAMSAT) daily rainfall estimates over Africa at a 4 km resolution. When aggregated over time and space, TAMSAT has been shown to have good estimates over much of Africa, in comparison to ground-based observations (Maidment et al. 2017). On daily timescales, the occurrence is better represented than amount with the magnitude of high intensity rainfall events not captured. For these reasons, TAMSAT tends to be used to monitor drought rather than to provide real-time early warning of floods. The results of the study demonstrated how the use of TAMSAT data improved the results generated from JULES (Maidment et al. 2017; Pinnington et al. 2018).

One of the most infamous methods used that incorporate remotely sensed data is the Soil Water Assessment Tool (SWAT). This model has been studied extensively across the globe to assess the impact of land use conversions and climate change on hydrological responses. In Africa, 206 articles were published where the SWAT model was applied. Akoko et al. (2021) published a thorough review analysisng the application of the SWAT model in Africa and results show that the countries with the highest number of papers published were Ethiopia, Kenya, Tanzania, Tunisia, South Africa, and Nigeria with 69, 19, 15, 13, 13, and 7 papers, respectively. Various dataset inputs are needed for the SWAT model which include, hydraulic response units (HRUs), vegetation variables, such as the leaf area index (LAI), partial least square regression (PLSR) statistical model to evaluate water yield, surface runoff, and base flow, curve number (CN) method within the SWAT model used to estimate surface runoff at the watershed scale in tropical regions (Akoko et al. 2021; Krysanova and White 2015). In a study conducted by Le and Pricope (2017), Western Kenya, the SWAT model simulations for streamflow were poor with rainfall gauge station data but improved significantly with the climate forecast system reanalysis (CFSR) and climate hazards group infrared precipitation with station (CHIRPS) datasets. Hence, showing the valuable addition of remotely sensed datasets in hydrolic models. Based on the various techniques used to determine hydrological responses through remote sensing, majority of the available techniques are used to assess run-off and streamflow with very limited sole focus on ET.

Various techniques, such as micro-meteorological approaches, have been extensively applied and shown to be invaluable for the estimation of ET (Gokool et al. 2016). The conventional point-based ET estimation methods do not capture large spatial scale variability of ET and are very difficult to obtain due to time and cost constraints (Ramjeawon 2016). Furthermore, Li et al. (2009) adds that these conventional techniques are often complex to apply, data-intensive and generally limited to small spatial scales and homogenous land covers. Gokool et al. (2016) further states that advancements in satellite earth observation and GIS technologies over the past 4 decades have provided a useful alternative to researchers, providing useful information for the quantification of various hydrological processes. Evapotranspiration by remote sensing provides an area-based estimation that can be updated frequently as it has the capability of quantifying the vegetation characteristics including species composition, vegetation type and moisture status for a broad area, more accurate results would be obtained (Nouri et al. 2013). Liou and Kar (2014) states that remotely sensed images have provided a promising source of data for mapping regional and meso-scale patterns of ET on the Earth's surface. The energy balance approach holds great promise for application in sub-Saharan Africa, for example this approach can be seen in studies conducted in South Africa (Gibson et al. 2013; Shoko et al. 2015) and Kenya (Odongo et al. 2019). One of the recent and most adequate algorithms for daily ET estimation includes the Surface Energy Balance System (SEBS) model, which was developed by Su (2002) at the ITC in Netherlands. It has since been studied intensively as shown in Table 3. SEBS takes into account different land surface, physical and biological parameters and these parameters are best suited as input features in the SEBS model for reliable results in comparison with other relevant models (Elhag et al. 2011). Shoko (2014) states that the SEBS model estimates heat fluxes, using remotely sensed data (i.e., land surface temperature (LST), albedo, emissivity, fractional vegetation cover (FVC), leaf area index (LAI), normalised difference vegetation index (NDVI)) and meteorological data (i.e., temperature, humidity, wind speed and pressure) at a reference height. The environment in which the SEBS model has been most extensively applied is includes the agriculture sector with variations of sparsely vegetated and barren land, forests, wetlands, and, most recently, urban areas and grasslands (Gibson et al. 2013). Although remote sensing cannot directly quantify total evaporation from space, satellite data provide inputs for its estimation and when combined with ground-based meteorological observations, an accurate estimate of ET can be produced (Liu et al. 2003).

5. Progress in the remote sensing of hydrological responses

Many of the hydrologically based models used to determine hydrologic responses have been developed over the last few decades. Due to advancements in technology, there have been modifications to the models over time in order to improve accuracy and results of run-off and streamflow. An example of this includes the SCS-CN model, which was introduced in 1954 and has since been modified to the SCS-CNx model (Bartlett et al. 2016), in order to extend beyond the limitations of the SCS-CN model. Unlike the traditional SCS-CN method, the extended SCS-CNx method consists of equations for the fractions of watershed area producing either pre-threshold or threshold-excess run-off or the corresponding average run-off value (i.e., the runoff curve). This new spatial description of run-off may allow for a more realistic extension of the SCS-CNx method to run-off related processes.

Another example includes the SWAT tool which started in the early 1990s by merging SWRRB (Simulator for Water Resources in Rural Basins) and ROTO (Routing Outputs to Outlet) to overcome limitations of the oversimplified flood routing and restrictions on a number of sub-basins in SWRRB, and to facilitate the model parameterization for larger basins with a variety of land uses and soil types (Krysanova and White 2015). The GIS interfaces for the SWAT model have kept pace with model development, progressing from a GRASS GIS to the current ArcGIS 10.2 interface. During this time, SWAT has undergone continuous review, testing, modification and enhancement.

The progress of ET estimation stems from conventional methods, which were discussed by Ramoelo et al. (2014) who provided a comprehensive review on three different in-situ methods used to estimate ET. Direct measurements are conducted with porometry and lysimeters. Atmospheric measurements, include energy balance and micrometeorological techniques, such as Bowen ratio, eddy covariance, scintillometry, as well as methods based on weather data. For example, used for the calculation of the Penman-Monteith reference grass evapotranspiration (ETo) and crop coefficient. Lastly, these methods are based on soil measurements and the application of the soil water balance. However, it was discovered that these in-situ methods estimate ET at a small scale (< 5 km) and are limited due to land surface heterogeneity. In addition, in-situ instruments cannot be installed at sites, which have restricted access, therefore limiting the estimation of ET in these areas and in some cases; they are costly and require maintenance (Ramjeawon 2016). Various remotely sensed ET products currently exist and have been derived from observations from a range of satellite families, such as the Moderate Resolution Imaging Spectroradiometer (MODIS) and Landsat satellites. Progress in Global Land Evaporation Amsterdam Model (GLEAM) is evident. GLEAM is a set of algorithms for estimating terrestrial evaporation and soil moisture. The approach was revised in 2014 (Miralles et al. 2011) and is currently on its third version (Martens et al. 2017). The current GLEAM product consists of a series of microwave (C- and L band) measurements of vegetation, soil moisture and precipitation, as well as thermal observations of land surface temperature (LST), from sensors such as MODIS and the Soil Moisture Ocean Salinity (SMOS) mission (West et al. 2019). However, the developments in satellite remote sensing provide better spatial explicit datasets for hydrological modelling. For example, Shoko (2014) used MODIS and Landsat observations to determine the effect of spatial resolution in remote sensing estimates of ET. However, results show that ET estimates generated from Landsat 8 were more favourable than MODIS and this could be attributed to better spatial resolution (30 m spatial resolution which enables Landsat 8 to detect small variations in total evaporation, when compared to the 1000 m MODIS resolution) and spectral properties. Landsat satellites have been used in the development of new, higher resolution, monitoring approaches (Young et al. 2017). Over the years the Landsat series has advanced since the launch of the series in 1972 with the addition of the thermal band on Landsat 3 (launched in 1978), which was later enhanced on Landsat 4 (1982) onwards and high resolution (30 m visible and 120 m thermal) retrievals of land classifications and LST were made possible. Since 1999, two more series were launched namely Landsat 7, which included a panchromatic band with increased spatial resolution and Landsat 8, which is equipped with its Operational Land Imager (OLI) and Thermal Infrared (TIRS) sensors. These improvements have led and aided in the retrieval of relatively high-resolution evapotranspiration estimates (e.g., Shoko et al. 2016).

Several studies (Jarmain et al. 2009; Li et al. 2009; Elhag et al. 2011; Gibson 2013; Gibson et al. 2013; Jin et al. 2013; Nouri et al. 2013; Ramoelo et al. 2014; Ferreira et al. 2016; Gokool et al. 2016; Zhang et al. 2016) reviewed different remote sensing techniques used to estimate ET. These can be classified into; (i) empirical methods that involve the use of statistically-derived relationships between ET and vegetation indices such as the normalized difference vegetation index (NDVI) or the enhanced vegetation index (EVI), residual methods of surface energy balance which include the Surface Energy Balance Algorithm over Land (SEBAL), Surface Energy Balance System (SEBS) and Mapping EvapoTranspiration at high Resolution with Internalized Calibration (METRIC), (ii) physically-based methods that involve the application of the combination of Penman-Monteith and Priestley-Taylor types of equations, and data assimilation methods adjoined to the heat diffusion equation and through the radiometric surface temperature sequences. The use of remotely sensed data to estimate ET started from the 1980s and has since seen the development of various approaches and models. However, there is no consensus on which approach or model is best because each of these approaches/models has its own advantages and limitations. According to Zhang et al. (2016), the Surface Energy Balance (SEB) method is the earliest remote sensing-based ET estimation method and combines the SEB expression and land surface flux equations, with remotely sensed temperatures. Three of the main Terra sensors (MODIS—Moderate Resolution Imaging Spectrometer, ASTER—Advanced Space borne Thermal Emission and Reflectance Radiometer, and MISR—Multi-angle Imaging Spectro radiometer) have been identified as being particularly useful in the remote sensing of large-area land cover and land use changes and vegetation dynamics studies (Khorram et al. 2016). Other surface energy balance methods have since been developed and have proven to be successful in estimating ET. One of these methods in particular is the SEBS model. There is a need to evaluate global remote sensing products again at long term monitoring sites in sub-Saharan Africa. Over the recent years, the use of surface energy balance algorithms based on remote sensing data, has been shown to be quite promising for the estimation of actual ET on both regional and local scales (Ferreira et al. 2016). Shoko et al. (2015) states that energy balance models that estimate ET, have been proved to be beneficial and accurate in estimation of ET. One of the recent and most adequate algorithms for daily evapotranspiration estimation for agriculture lands is the Surface Energy Balance System (SEBS) developed by Su (2002). Since the SEBS model was proposed, it has been used and tested in several studies (Elhag et al. 2011; Gibson et al. 2011; Shoko et al. 2015).

Satellite earth observation has shown great potential in providing information at large geographic scales. Furthermore, it allows data to be captured in data-scarce regions and can provide time-series data easily, due to the periodic updating of information (Gokool et al. 2016). Remote sensing images can effectively record land use situations and provide an excellent source of data, from which updated LULC information and changes can be extracted, analysed and simulated efficiently. In addition, GIS provides a flexible environment for collecting, storing, displaying and analysing digital data necessary for change detection (Liping et al. 2018). The use of remote sensing-based methods for estimating ET has gained momentum in the past 5 years and holds great potential for monitoring water use and ET across various spatial and temporal scales, and for being integrated into operational water resource management systems in sub-Saharan Africa (Gibson et al. 2013). Findings based on studies conducted in South Africa show that MODIS data did not adequately derive accurate inputs for estimating sensible heat flux. However, at Landsat resolution, it may be possible to retrieve estimates that are more accurate (e.g., Shoko et al. 2015; Gokool et al. 2016).

6. Strengths and limitations of remotely sensed hydrological responses

Remotely sensed-based methods have the ability to accurately reproduce hydrological responses over a wide range of conditions, at both the satellite overpass time and daily time scales, at a cost-effective manner. The use of geographic information systems (GIS) and remote sensing were found to be helpful tools to detect and analyse spatiotemporal land use/cover dynamics, using the SWAT tool (Tadele and Förch 2007). Within the past two to three decades, satellite remote sensing retrieval of ET has become a popular tool and study area due to its high cost-effectiveness, wide and repeatable coverage, and reasonably favourable accuracy (Zhang et al. 2016). In addition, ET estimation using satellite imagery is the most efficient and economic technology that can be employed for a broad range of pixels to global scales (Nouri et al. 2013). Furthermore, the advances in technologies, as well as the need for timely and accurate estimates of ET have resulted in immense improvements to approaches that are based on remotely sensed data (Shoko et al. 2015).

According to Roy and Inamdar (2019), the benefits of employing satellite-based ET estimation techniques can be invaluable in improving water resource management. The integration of different types of remote sensing data, along with ancillary data from different sources, is driving many new scientific investigations. Remote sensing data is also helping to develop a better GIS which in turn can be used for education, land management, natural resources management, environmental and aeronautical applications. With these recent advances in remote sensing there have been many different approaches and techniques for estimating evaporation using earth observation data. However, there is no consensus on which approach or model is best. This is because each of these approaches/models has its own advantages and limitations. Eludoyin et al. (2019) reviewed that developing countries, such as those found in sub-Saharan Africa might require a huge budget for retrieving high resolution remotely sensed images.

Recent developments in the use of surface energy balance models that use satellite remote-sensing data (visible, near-infrared and thermal infrared imagery) now make it possible to quantify actual ET of various land uses simultaneously over space and time (Meijninger and Jarmain 2014). This has led to the possibility of obtaining land surface information at spatial resolutions from 0.5 m − 5 km, with frequent revisit times (up to every 15 minutes) (Gokool et al. 2016). The SEB models are the earliest of remote sensing methods to map ET. According to Ramjeawon (2016), in South Africa, The SEBAL model is the most applied model followed by SEBS, METRIC and VITT. Ramjeawon (2016) further discusses the benefits of each model. The advantages of the SEBAL model include small amounts of ground-based data, the presence of an automatic calibration within the model which reduces the need for surface temperature correction and the internal calibration is possible for each image being analysed. Favourable characteristics of the SEBS model include an open-source model which is available in free software namely, ILWIS, there are physical parameterizations used to solve the energy balance in SEBS and fewer assumptions can be concluded compared to other techniques. The METRIC model can be calibrated, using ETo instead of evaporative fraction. The advantage of the VIT trapezoidal model is that it does not require a large number of pixels like the VIT triangular method.

According to Gokool et al. (2016), one of the main challenges of remotely sensed ET methods involves the availability of good quality imagery for the running of ET models. The revisit and repeat cycles of satellite sensors, as well as clouds, influence the number of images which can be used for a particular period of interest. This may limit the feasibility of applying a satellite-based approach for the estimation of ET in regions, which experience rapid temporal changes, such as irrigated agricultural fields. Limited temporal availability of imagery can be a limiting factor to the application of satellite data for hydrological modelling applications or decision support systems, which require daily continuous data as input. Furthermore, Gibson et al. (2013) states that there is limited availability of high resolution thermal infrared imagery which is essential when using an energy balance approach, the scattering and absorption of radiation by clouds, and insufficient attention given to the spatial interpolation of weather station data across a larger area. Coarse spatial resolution imagery can be useful for routine monitoring and estimation of ET due to its high temporal resolution. However, the spatial resolution associated with these images is generally too low to provide beneficial information for hydrological applications, as pixel sizes often exceed the size of the area under observation. While moderate and fine spatial resolution imagery can be used to overcome this limitation, their limited temporal resolution does not allow for operational monitoring and estimation of ET (Gokool et al. 2016). Ramjeawon (2016) adds that one of the disadvantages of remote sensing is the amount of data required. Data required needs to be collected from several sources and is usually obtained from satellites or meteorological data in the form of field data. In addition, the user can be faced with both scientific and practical difficulty during the data collection phase. The scientific problem faced by users is the use of data obtained from various spatial and temporal scales. This requires users to alter the data into the same spatial and temporal scale before using the data and the practical problems faced by the user include data collection, the complexities involved using GIS, such as merging, and formulating the required algorithms to determine ET. The final ET result is dependent on the accuracy and reliability of the input data used.

7. Discussion

Determining the impact of LULC change and climate variability, on hydrological responses, using remote sensing has been extensively studied. However, understanding the impact of these variables on ET remains limited when compared to surface run-off and streamflow. LULC change and climate variability both contribute to serious deterioration of the natural environment, hydrologic cycle and water resource availability, as proven in various studies (Tables 1 and 3). LULC change has been monitored and mapped for decades using remote sensing and GIS. Earlier methods consisted of integrating historical topographical map data, field observations and aerial photography in order to produce LULC maps (Shalaby and Tateishi 2007). Overtime, there has been advancements in LULC classification methods, which aim to continuously improve accuracy in LULC mapping, in conjunction with advancements in satellite imagery. Accurate LULC mapping is required in order to assess the effects of this change on hydrology and water resource availability. Futhermore, LULC maps provide essential information for the planning and management of urban, natural resources, and ecosystems. Hence, it is essential to ensure that advancements and progress in remote sensing are studied extensively to enhance future monitoring. Climate variability has also contributed to severe effects on water resources in water scarce regions and has been studied as a stand-alone impact on hydrology and it has been studied in conjunction with LULC change. Because of human population expansion, issues such as urban heat islands have contributed towards climate variability. Other negative effects include increasing sea surface temperatures and LST that have caused variation in temperature and precipitation. In addition, climate variability has shown to worsen droughts and flooding. Therefore, there is a need to understand and quantify the effects of climate variability on hydrology. Although the effect of LULC and climate variability has been applied on hydrological responses, there is still a limited number of studies that focus on their effect on ET.

Remote sensing has proved to be beneficial in many hydrological monitoring studies as it is cost-effective and proves to be a reliable alternative for representing spatial variability. Various hydrological models have applied remote sensing to determine the effect of LULC change and climate variability on run-off and streamflow. ET is a less common hydrological component that has been studied with regards to the impact of LULC and climate variability on hydrological responses. However, the application of remote sensing in estimating ET has shown to be promising. The SEBS model is a common technique used to estimate ET as it incorporates remotely sensed data and meteorological data to produce daily ET regionally. Although remote sensing has limitations, present day progress of sensors allows for more accurate representation of spatial ET which can be used by land and policy managers to protect and conserve water resources.

8. Conclusion

A review of literature demonstrates that land cover conversions and climate variability have been proven to have significant impacts on hydrological processes. The sub-Saharan Africa is highly dependent on water resources, yet this part of the continent is said to be the most vulnerable to LULC change and climate variability. Changes in land use land cover, as a result of rapid population growth and increasing demand for agricultural land to meet the needs of human population, has in turn affected run-off, streamflow, water quality, sediment yield, discharge and total evaporation in catchments. In addition to LULC changes, climate variability has resulted in changes in hydrological responses because of temperature and rainfall changes over a time because of global warming. LULC modelling has evolved and progressed over the last few decades with current studies showing advancements in satellite imagery, classification methods and accuracy assessments. Various methods incorporating remotely sensed data have been applied to determine hydrological responses in sub-Saharan Africa, such as the SCS-CN, JULES and SWAT method. Literature shows that these methods focused on estimating hydrological parameters such as run-off and stream flow with limited focus on ET. Over the recent years, remote sensing has proved to be effective in the estimation of ET due to technological advancements and its cost-effective tendency. Further, the SEBS tool has been applied extensively because of its performance. Currently, the model is considered a highly used remotely sensed technique in estimating total evaporation. Although remote sensing has many advantages; cloud cover, poor temporal and spatial resolutions are a few of the limitations that should not go unrecognised. In water scarce countries, such as those in sub-Saharan Africa, there is a need for further research on the effects of LULC and climate variability on ET using multi-spectral imaging to ensure appropriate water resource management.

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Data availability

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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