

# The Application of Satellite Imagery in Surface Water/Lake Modelling: A Review of Previous Studies on Lake Tana and Its Basin

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**Abstract:** Satellite images give a synoptic view of target areas, measure target surface changes and provide the information needed for hydrological studies, river or Lake Basin management, water disaster prevention, and water management. Lake Tana is located at an altitude of 1830 m and latitude longitude of 11.27°N and 37.10°E. The lake is the source of the Blue Nile River and it is the largest lake in Ethiopia with a surface area of 3,150 km<sup>2</sup>, a maximum length and width of 78 and 68 km respectively. In the past, several studies have been published on Lake Tana and its basin in a scattered manner. This necessitates state of the art review that highlights achievements, models, algorithms, and identify gaps in knowledge. Different types of hydrological models have been applied. The majority of the recent studies utilized simple conceptual and statistical approaches for trend analysis and water balance estimations, mainly using rainfall, temperature and evapo-transpiration data. To a greater extent, recent studies have used advanced semi-physically or physically based distributed hydrological models driven by high resolution temporal and spatial data for diverse applications. A review of the methods used and the role of satellite remote sensing in this regard to understand the hydrology of Lake Tana and its basin are presented.

**Keywords:** Satellite Imagery, Surface Water/Lake Modeling, Lake Tana

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## 1. Introduction

Ethiopia is located in East Africa and covers a total surface area of 1.1 million square kilometers. Water bodies cover only 0.7% of the area of the country with 10 lakes. Most of them are located in the Rift Valley, and together they have a total surface area of 7,500 km<sup>2</sup>. By far the largest water body is Lake Tana (50% of the total lakes area) located outside the Rift Valley on the northwestern plateau [23]. It is located at an altitude of 1830 m and 11.27°N and 37.10°E of Ethiopia and it is the source of the Blue Nile River and it is the largest lake in Ethiopia with a surface area of 3,150 km<sup>2</sup>, a maximum length and width of 78 and 68 km respectively. A bathymetric map produced by [64, 73] shows a gentle slope of the saucer shaped Lake Bottom, which is covered with soft

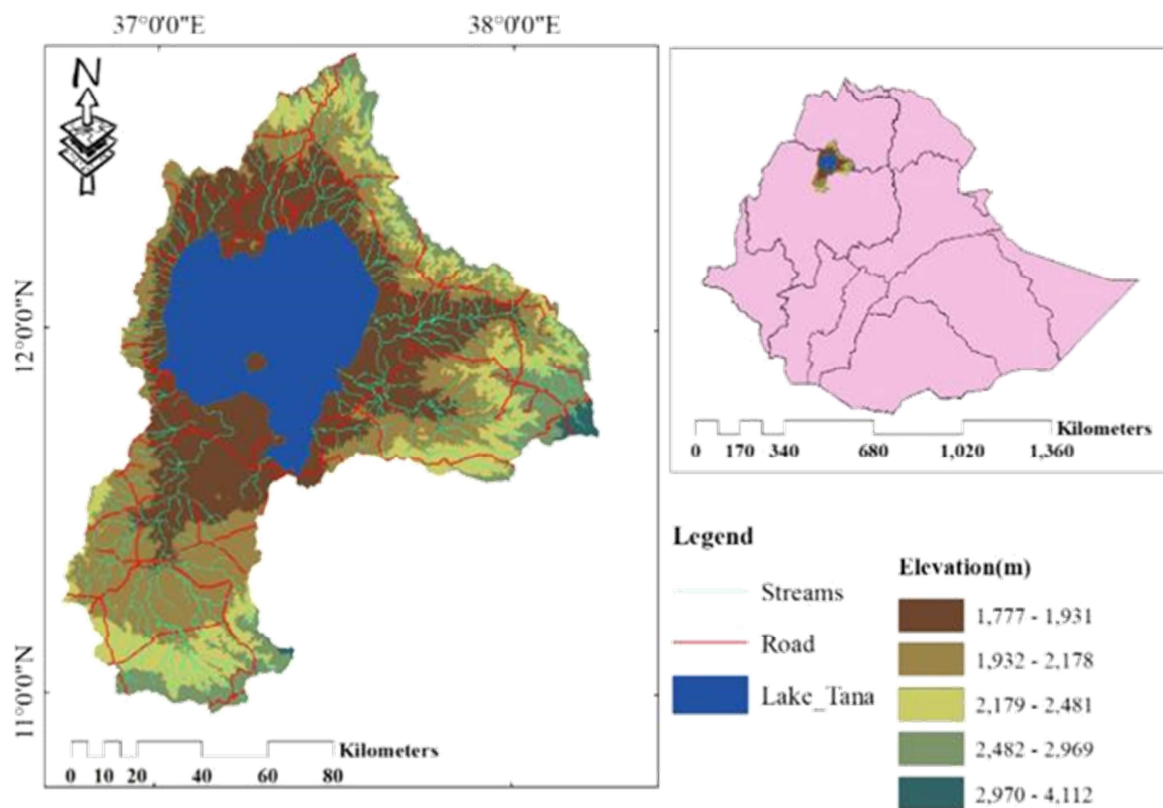
sediments. The shallow littoral zone (depth 0 - 4 m) is relatively small, ca. 10% of the total surface area of the lake. The sub littoral zone contains no macrophytes and occupies ca. 20% of the lake area (depth 4 - 8 m), whereas the oceanic zone is 70% of the lake surface area and relatively deep (depth 8 - 14 m). Lake Tana has been formed because of damming by lava flow during the Pliocene [63] but the formation of the depression itself started in the Miocene [21].

## 2. Review on Satellite Image Processing Application

Hydrological data collection remains a difficult task now a day due to non availability of measurement devices,

inaccessibility of the terrain and limitations of space/time [57, 12]. A good alternative to overcome these difficulties is the use of satellite remote sensing images, which can give a synoptic view of target areas and measure target surface changes and therefore provide the information needed for hydrological studies, river/ lake basin management, water disaster prevention and water management, etc [19]. Lake Tana receives about 90% of the inflow from the four rivers. The local and regional groundwater inflow contributes only 3% and 7%, respectively [16]. The lake is geologically dammed by quaternary and tertiary basalts in the south and western part where the out flowing Blue Nile River drains out [50]. The damming has cut of any oozing out flow which simplifies modeling of the lake stage [44]. The climate of Lake is characterized by a major rainy season (kiremt), during June - October, short rain season during February and

dry season November to January. The average annual rainfall in the lake area over 1997 - 2000 was 1418 mm. The water level of the lake fluctuates with rainfall up to 1 m. Maximum water temperature, as a monthly average, ranged between 21°C and 26°C over 1997 - 2000. Water temperatures varied between narrow limits, with lowest values in January, a sharp increase in February, peak values in May and sharp decline with the big rains in June - July [23]. Several methods have been used to delineate the hydrological extent from satellite data; such as the utilization of multi-polarized advanced satellite images, application of a statistical active control model, multi-temporal image enhancement and differencing, histogram thresholding/clustering, radiometric thresholding, pixel based segmentation, and use of artificial neural networks [67].



**Figure 1.** Location map of Lake Tana basin [51].

**Table 1.** Some satellite missions and sensors used for hydrological studies.

Satellite mission	Sensor	Data Record Period
Nimbus -7	Coastal Zone Color Scanner (CZCS)	October 1978 to June 1986
Adeos	Ocean Color and Temperature Scanner (OCTS)	October 1996 to June 1997
OrbView2	Sea wifs	August 1997 to February 2011
Envi sat	Meris	March 2002 to May 2012
Terra	Moderate Resolution Imaging Spectro radiometer (MODIS)	December 1999 to present
Aqua	MODIS	July 2002 to PRESENT
ISS	Hyper spectral Imager for the Coastal Ocean (HICO)	September 2009 to September 2014
SNPP	Visible Infrared Imaging Radiometer Suite (VIIRS)	October 2011 to present
COMS	Geostationary Ocean Color Imager (GOCI)	May 2011 to PRESENT
SACD	AQUARIUS	June 2011 to June 2015
Sentinel3	Ocean and Land Color Instrument (OLCI)	February 2016 to present

### 3. Scope of Studies on Lake Tana

Some researchers have evaluated the temporal trajectory change of the lake surface area eg. [89], the majority of the investigations were on the exploration of seasonal and annual trends of rainfall in the Lake Tana basin (LTB) and their connections with global sea surface temperatures (SSTs) e.g.

[43, 83], the evaluation of hydrological impacts of climate and LULC changes on the water balance of the Lake was also made in several studies e.g. [65, 61], while others focused on simulating water balance at a daily time step by accounting for all inflow and outflow processes of lake Tana e.g. [14, 72]. The comprehensive list of studies and their objectives are given in Table 2.

**Table 2.** Overview on previous studies and their objectives.

Article	Study objectives	References
Temporal and special phytoplankton biomass dynamics in southern Gulf of LakeTana, North western Ethiopia	Determining the special and temporal variation of phytoplankton biomass of the gulf (southern gulf of lake Tana)	[37]
Temporal Trajectory Analysis of Lake Surface Area: Case study on Lake Tana, Ethiopia	Evaluating the temporal trajectory change of the lake surface area of lake Tana	[89]
Analysis of Rainfall Trends and Its Relationship with SST Signals in the Lake Tana Basin, Ethiopia	Exploring seasonal and annual trends of rain fall in lake Tana basin and their tele- connection with sea surface temperature	[83]
Hydrological Impact Assessment of Climate Change on Lake Tanas Water Balance, Ethiopia	Evaluating the hydrological impacts of climate change on the water balance of Lake Tana in Ethiopia.	[65]
Mapping the vegetation of the Lake Tana basin, Ethiopia, using Google Earth images	Mapping the vegetation of Lake Tana basin through visual interpretation using high spatial resolution images to provide detailed information of the actual vegetation state for planning conservation and restoration.	[77]
Estimation of Lake Outflow from the Poorly Gauged Lake Tana (Ethiopia) Using Satellite Remote Sensing Data	Investigating the water balance of lake Tana at monthly and annually time scale.	[28]
Water Hyacinth Coverage Survey Report On Lake Tana Biosphere Reserve. Technical Survey Report Series 2	To know and report the water hyacinth coverage of lake Tana	[8]
Stage level, volume, and time frequency information content of Lake Tana using stochastic and wavelet analysis methods	Simulating the lake level, specifically extreme events of the lake variation.	[14]
Hydrological Modelling in the Lake Tana Basin, Ethiopia Using SWAT Model	Testing the performance and feasibility of the SWAT mode for prediction of stream flow in the Lake Tana Basin.	[74]

### 4. Data and Methods Employed in Past Studies

#### 4.1. Data

Observations are from many different sources, including satellites, ships, ground stations, and radar. Currently, earth system research laboratory, physical sciences division (PSD) makes available these reanalysis datasets to the public. Reanalysis is a method to reconstruct the past state of the atmosphere and oceans in a coherent way by combining available observations with numerical models [7]. The Land sat satellites and other remote sensing data with high spatial resolution and frequent coverage have been widely used for a variety of space and land surface dynamics, monitoring applications such as change detection [22, 86, 18, 56], land cover classification [46, 88], biomass estimation [90, 55], leaf

area index retrieval [17, 30], vegetation phenology monitoring [75], and drought monitoring [32]. The Land sat satellites and remote sensing data are needed for monitoring heterogeneous landscapes or rapid surface changes [91]). Seasonal time series data from satellites are highly desired by researchers since they contain the temporal aspects of natural phenomena on the land surface, which are extremely helpful for discriminating different land cover types [92], monitoring vegetation dynamics [75], estimating crop yields [48], assessing environmental threats [34], exploring human nature interactions [93], and revealing ecology climate feedbacks [68]. For analyzing lake Tana and its basin many types of data were employed to assess the physical, climatologically, hydrological and environmental phenomena of the lake and its basin, such as monthly rainfall and precipitation data e.g. [28], weather and soil data e.g. [74], and surveying and GPS data e.g. [8]. Table 3 lists the data types of some selected studies of Lake Tana and its basin.

**Table 3.** The data used by some researchers on Lake Tana and its basin.

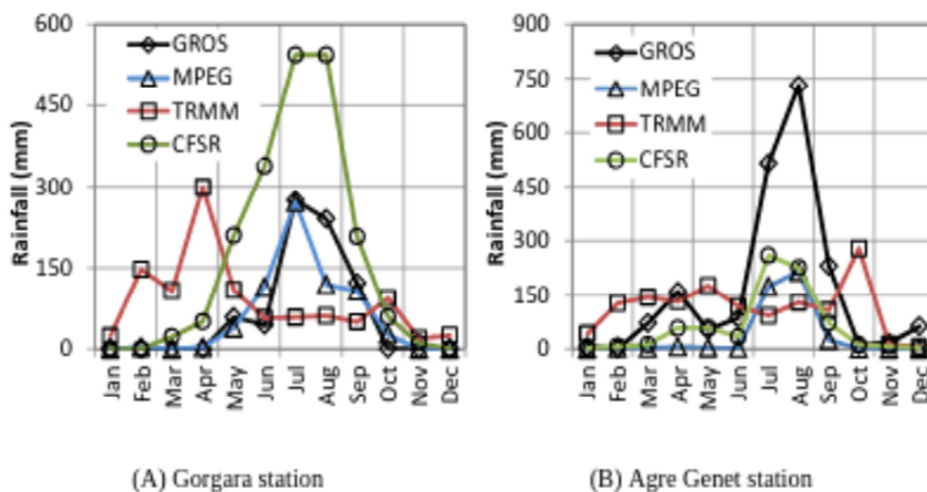
Data used	Study period	Focus area	References
Rain fall data from NMA and SST data from NOAA	1979 - 2015	Lake Tana basin (LTB)	[83]
Daily records of metrological and hydrological data	1981 - 2010	Lake Tana basin (Adet, Bahir Dar, Dangila, Debre Tabor and Gondar)	[65]
Global Circulation Model (GCMs) data	2010 - 2100	Lake Tana Basin (Gilgel Abay River, Upper Blue Nile Basin)	[26]
Land sat images, lake level, rain fall, temperature and population	for the last 30 years	Gilgel Abbay Catchment from southern part of Lake Tana	[61]
Daily, maximum and minimum temperature, wind speed, relative humidity, sun shine hours and daily water levels of Lake Tana	1994 - 2003	Lake Tana basin Catchments (Ribb, Gilgel Abay, Gumara, Megech, Koga, Kelti)	[72]
Daily climate projections data from global climate models (GCMs) and hydrological changes data using the Soil and Water Assessment Tool	1961 - 2000	Lake Tana Basin	[74]

Data used	Study period	Focus area	References
(SWAT)			
Monthly rain fall data and monthly precipitation data		Lake Tana	[28]
Time series of monthly flow data, daily flow series dataturbine discharge data	1959 - 2006	Lake Tana basin	[58]
High spatially resolution images and field survey data		Lake Tana basin	[77]
Average annual and daily rain fall data	1994 - 2010	Source of the blue Nile river (Lake Tana basin)	[84]
Satellite images and filed observation data	1985 and 2011	East of lake Tana (Tana mitsil ikebele)	[36]
Satellite images and filed observation data	1973 - 2011	Lake Tana basin	[69]
Black and white photography and land sat satellite images	1957 - 2014	Lake Tana water shed (Gelda catchment)	[29]
Aerial photography and multispectral spot images	1957 - 2005	Lake Tana basin (Gumera watershed)	[85]
Farmer interview, remote sensing images and current gully measurement	2005 - 2008	Debremawi watershed (south of lake Tana)	[79]
Hourly rain fall data and cloud temperature indices		Lake Tana basin	[43]
Satellite images, Climatic data and TM data	1985 - 2011	Angerb watershed (upper Tana basin)	[59]
Land sat satellite images, temperature and rainfall data	1973 - 2008	Gilgel Abbay catchment of lake Tana	[62]

#### 4.2. Spatial and Temporal Precipitation Data Analysis

Precipitation is a major component of the water cycle and is responsible for depositing approximately 505 000 km<sup>3</sup> (or on average 990 mm) of the freshwater on the plan [70]. It is one of the major water balance components of the global water budget. Although the spatial and temporal variability of precipitation is important, unless large numbers of rain gauge stations are available, capturing variability is difficult [13, 66].

Moreover, ground based rainfall observation station networks are often unevenly and sparsely distributed in developing countries [49]. The monitoring of precipitation by satellites and that at weather stations has different spatial and temporal characteristics [87]. The TRMM precipitation had difficulties in detecting precipitation at high elevations, especially in the rain shadows [5]. However, this effect may have been somehow overcompensated by the TMI or IR component in the 3B42 V5 dataset [87].

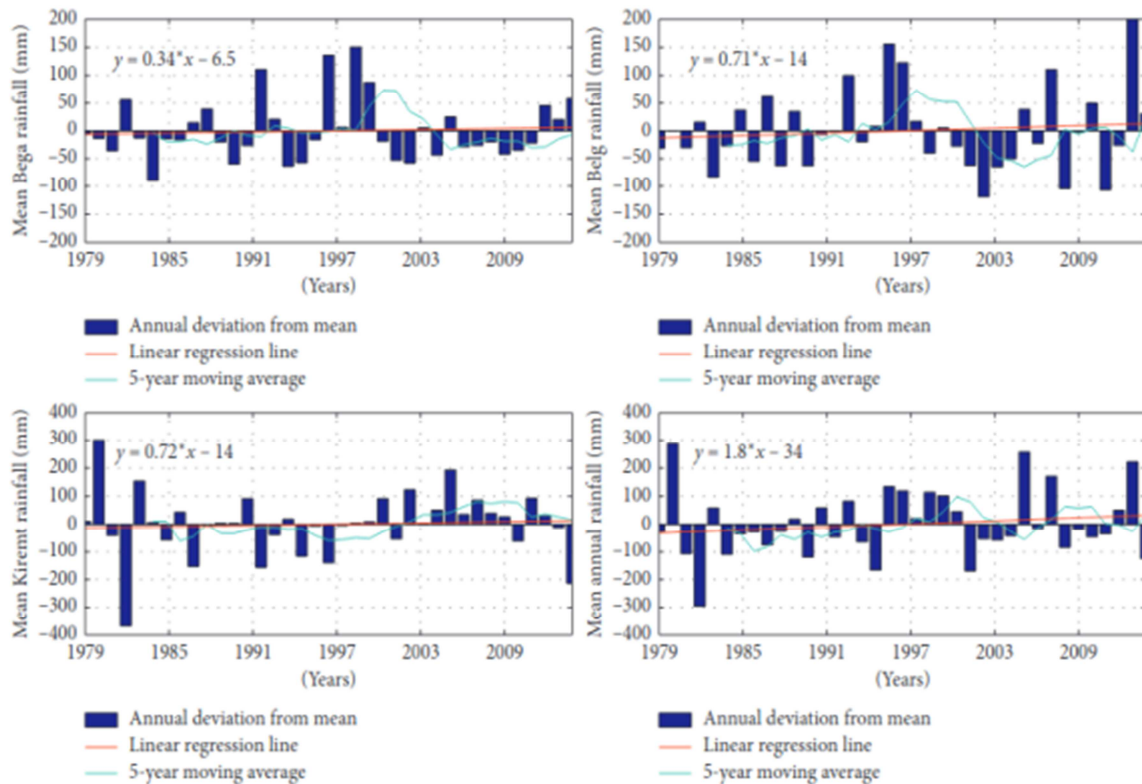


**Figure 2.** Temporal distribution of gauged rainfall and satellite rainfall estimation from the Tropical Rainfall Measuring Mission (TRMM), Multi-Sensor Precipitation Estimate Geostationary (MPEG) and Climate Forecast System Reanalysis (CFSR) for Gorgara and Agre Genet stations (year: 2010) [84].

#### 4.3. Big Data Approach

Earth observation data, admitting satellite images, are an example of a big data source which can be obtained at no cost, for a long time series, and used to develop statistics and indicators to measure sustainable development [42]. In 2017, the United Nations project team on satellite imagery and geospatial data published a report on the feasibility of using earth observation data to produce official statistics, including statistics relevant to SDGs such as agricultural indicators and land cover

[42]. There are many useful resources on the topic of earth observation data for official statistics and SDGs, including satellite earth observations in support of the SDGs [45], Earth observation for water resources management [33], statistical analyses of satellite images, such as land cover, can be apply to Sustainable Development Goals (SDGs). The group on earth observation (GEO) has identified that several SDGs can be measured at some level using earth observation data [20].



**Figure 3.** Mean seasonal and annual rainfall and equivalent linear regression trend line and 5 year moving average line plotted for the different aggregated station data sets. (a) Bega. (b) Belg. (c) Kiremt. (d) Annual [83].

#### 4.4. LULC Change Analysis

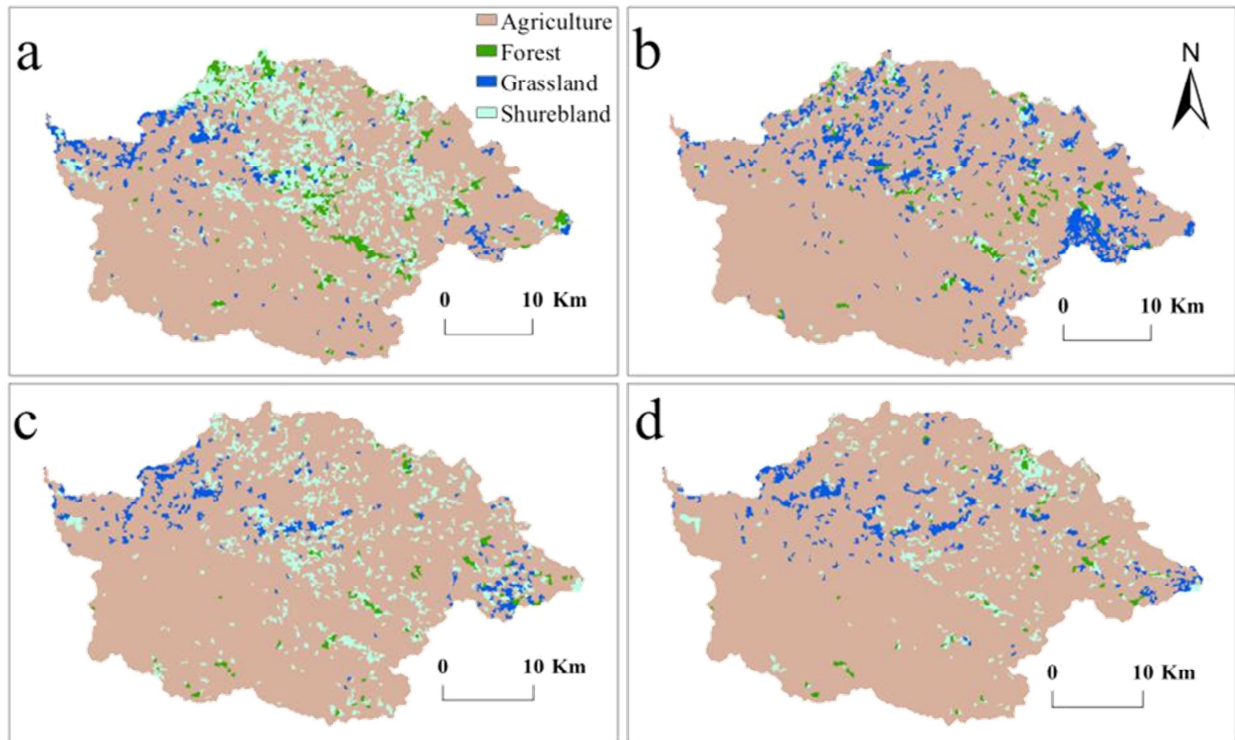
Land use/cover is two separate nomenclatures which are often used interchangeably [27]. Land cover adverts to the physical characteristics of earth's surface, captured in the distribution of vegetation, water, soil and other physical features of the land, including those created solely by human activities. On the other hand, land cover is defined by the attributes of the earth's land surface captured in the distribution of vegetation, water, desert, ice and the immediate subsurface, including biota, soil, topography, surface and groundwater and it also includes those structures created solely by human activities such as mine exposures and settlement [52] and [9]. Land use and land cover (LU/LC) change is a locally pervasive and globally significant ecological trend and has become an event of paramount importance to the study of global environmental change [39]. LU/LC change is progressively accredited as an important driver of environmental change on all spatial and temporal scales [81]. Land use/land cover change has been also creditworthy for altering the hydrologic response of watersheds leading to impacting river flows [40]. LU/LC complains in significantly to earth atmosphere interactions, forest fragmentation, and biodiversity loss. Thus, it has become one of the major issues for environmental change monitoring and natural resource management. That is why LU/LC change and its impacts on terrestrial ecosystems including forestry, agriculture, and biodiversity have been identified as high priority issues in global, national, and regional levels [31]. Land use/cover changes are the major

issues and challenges for the eco-friendly and sustainable development for the economic growth of any area. With the population explosion, human activities such as deforestation, soil erosion, global warming, and pollution are very harmful to the environment. This causes land use/cover changes with the demand and supply of land in different activities. Change detection in land use and land cover can be performed on a temporal scale such as a decade to assess landscape change caused due to anthropogenic activities on the land [41]. Land Use/Land Cover (LULC) change is one of the major worldwide environmental gainsays to humanity. It significantly affected hydrological response [82, 78], ecosystem services [53], and climate processes. The expansion of agriculture leads to a significant change in runoff and sediment load [38, 60]. Significant variation of evapo-transpiration has occurred due to LULC and leaf area index change [54]. Land use change can direct to a significant change in groundwater recharge and base flow [10] flood frequency and interval [4], peak runoff [2], and total suspended sediment and nutrient tightness [47]. Moreover, the land use change affects local, regional and global climate system [24], and degrades the health of a wetland ecosystem [3]. Land use change and climate changes could have interactive effects on the environment [11]. LU/LC dynamics is one of the major environmental troubles in Ethiopia. In congress to this, recent watershed based LULC studies of lake Tana depicted that land cover change is barbarous and there has been agricultural land size expansion at the expense of natural vegetation cover lands and marginal areas without any appropriate conservation measures [76, 6, 25, 35].



Similarly LU/LC dynamics of lake Tana basin shows that forest, shrub and grazing lands revealed negative rate of change between 1985 and 2011 while areas of cultivated land

and degraded land was increased accounted for 66.73% and 2.15% respectively in 2011 [36].

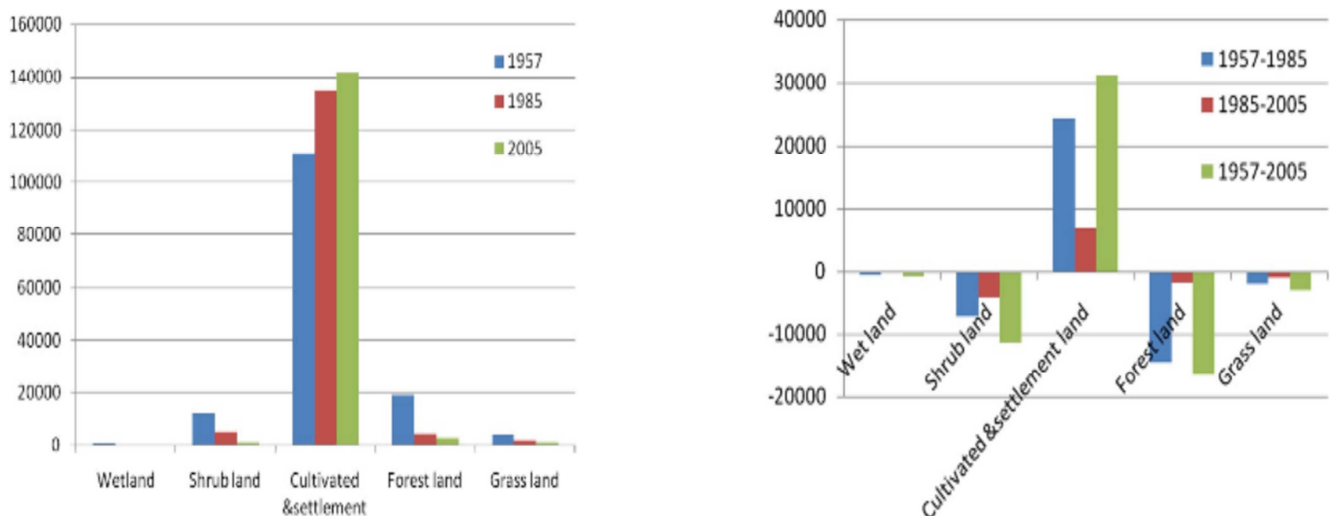


**Figure 4.** Land use land cover maps of the Gummara watershed: land uses for a) 1985, b) 1995, c) 2005, and d) 2015 [80].

#### 4.5. Advances in Models / Algorithms Used for the Studies

Different scholars applied different models to study lake Tana and its basin such as stochastic and wavelet analysis methods [14], statistical measures (coefficient of determination ( $R^2$ ), multiplicative bias (bias) and root mean square error (RMSE) [84], hybrid image classification method (unsupervised and maximum likelihood supervised

classification algorithm) [36] and [40], a conceptual water balance based model (HBV96 model) [72], land use/cover trend analysis [85], linear time series analysis (Linear regression) and supervised classification [62], Swat and Digital Elevation Model [74], etc. For more exhaustive descriptions of the algorithms or models the readers are directed to the original articles cited above and in Table 4.



**Figure 5.** (A) Trends of the LULC dynamics in the Gumara watershed and (B) Rate of change in LULC dynamics in the Gumara watershed [85].

**Table 4.** Sample models of previous studies on Lake Tana and its basin.

Models / Algorithms	Parameters used	References
Supervised classification method and Linear regression and t test	Temperature, Rain fall and Land cover and use dynamics	[62]
Supervised classification and Statistical method (Mann Kendall test)	Land cover change, Rain fall and Stream flow	[71]
Soil and water assessment tool (SWAT), Statistical analysis (static land use (SLU) and dynamic land use (DLU)) models	LULC change, Surface runoff, Evapo-transpiration and peak flow (hydrological response)	[80]
Parameter Efficient Distributed (PED) model	Rain fall, Temperature and suspended sediment concentration	[94]
Analytical Hierarchy process (AHP) approach	Litho logy, lineaments, drainage density, rainfall, slop, LULC and soils	[51]
Mass balance approach (modular three dimensional finite difference groundwater flow model and penmans, Meyers and Thornwaites methods)	Precipitation, river in flow and outflow, evaporation and ground water level, surface run o and rain fall	[15]
Had CM3 General Circulation model (GCM), statistical down scaling model and HBV semi distributed rain fall, surface run o model	Temperature and precipitation	[1]

## 5. Review out Puts

Satellite image processing application for space science, remote sensing and earth observation research has made an amazing advancement over the past decades. The deduction is that today's models can sensibly reproduce many facets of past and present hydrological, atmospheric, climate, environmental conditions and space phenomena. Possible future changes have been modeled while taking account of uncertainties regarding both knowledge gaps and management options. Space generated knowledge is manifestly important to society for managing our natural resources, environment, space, and atmospheric phenomena and further work is needed. The space program, which started with basic science questions, and related programs throughout the past decades have now afforded several achievements that are of great practical importance such as Meteorological, atmospheric, space and remote sensing databases are available to the research community, partly as station data, including a growing number of freely available gridded datasets on decadal and centennial time scales. These freely available datasets powerfully back up the development of accurate forcing functions for modeling and statistical analysis. We better understand how large scale temperature, rainfall, LULC dynamics, stream flow, evapo-transpiration, surface runoff, suspended sediment concentration, precipitation, and river inflow outflow circulation affects the special and temporal variation of phytoplankton biomass of the lake and its gulf, the temporal trajectory change of the lake surface area, the climate change and the water balance of Lake at monthly and annually time scale. We have an improved understanding of the methods and models or algorithms used to study the lake and its basin. We have also improved our understanding from the direction of different sources of data sets and data sources which are applicable for the study of lake or sea surface dynamics, TSS dynamics of lake or sea surface, the turbidity of lake or sea surface, the impacts of LULC on lake or sea surface change and the link between lake or sea surface change and environmental changes.

## 6. Research Gaps

Notwithstanding the progress made in satellite image processing application for space science and remote sensing and related research in the last decades. In our review, we have seen different techniques of satellite imagery data processing with different statistical analysis methods and different classification models to study Lake Tana and its basin and to assess the colligate between the lake, the environment, and ecosystems in it and around it. But currently there are several research gaps on the lake and its basin (spatially on the lake). For example, while salinity is an elementary factor controlling the ecosystem of the lake, the current understanding of salinity changes is still very limited and future jutting of salinity is somewhat unsealed. In addition, more elaborated probes of regional precipitation and evaporation patterns (including runoff), atmospheric variability, highly saline water inflows, exchange between sub basins, circulation, and especially the long term dynamics of the lake surface, the link between LULC of the basin and environmental change of the lake and LULC dynamics of the basin from space. Such studies will require more advanced measurements, especially those made using deep machine learning, satellite image analysis, remote sensing techniques and direct measurements of turbulence.

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