University of Nairobi

School of Engineering

DEPARTMENT OF GEOSPATIAL & SPACE TECHNOLOGY

Use of Remote Sensing to estimate Evapotranspiration (ET) for Water Resources Management: Case Study Ndaka-ini Dam Watershed

By

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F56/8140/2017

A project report submitted in partial fulfillment of the requirements for the Degree of Master of Science in Geographic Information Systems, in the Department of Geospatial and Space Technology of the University of Nairobi

MAY 2019

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DEDICATION

This project is dedicated to my family: my loving husband John, my children Precious and Charles who have given me great support and cooperation during this period of study.

ACKNOWLEDGEMENTS

I would like to thank the Almighty God for the gift of life and his plan upon my life. Lord, your grace has been sufficient for me.

My special appreciation and thanks goes to my supervisor Prof. G. C. Mulaku, who has been a great mentor for me. I would like to thank you for encouraging me in my research and for allowing me to grow as a research scientist. Your counsel and guidance from the coursework through to the research project has been invaluable. Your commitment has taught me a great lesson.

I am particularly grateful for the assistance by the chairman, Department of Geospatial and Space Technology, Dr. F. N. Karanja for the technical support and advice in formulation of this project idea. I also appreciate all the members of staff in the Department for the great support accorded during the study period.

I am greatly indebted to my great friends and colleagues Dr. Margaret Ndungo and Sabina Baariu for their continued friendship, encouragement and support; your insights will always be welcome. Thank you for the motivation and for always reminding me that the future is bright.

I wish to thank all my colleagues and classmates specifically Sabina, Simon and Gideon who were part of a private study group. It was worth being in the ‘county’ with you; your efforts will be rewarded. Thank you for being a great team and pushing on even during tough times.

A special thanks to my family. Words cannot express my gratitude for your love, encouragement, patience and prayers which kept me going. To my beloved husband John, children Precious and Charles; you have been a pillar of strength for me, may God reward you. To my parents, Mr. and Mrs. Ng’ang’a, I wish to thank you very much for your encouragement to go pursue my studies. To my sisters Trizah and Maggie, thank you very much for your continued support and encouragement.

ABSTRACT

Water is a very important commodity for sustaining life and also a key factor in sustaining agricultural production, energy production and other activities at optimal levels. Despite water being very important, the world including Kenya is far from being water secure which is proven by the demand of water already surpassing supply in many regions. Water availability has been acknowledged as a global problem and requires to be consistently assessed to support sustainable use. Assessing water availability is one aspect of water resources management. Evapotranspiration (ET) is the most problematic constituent of the water cycle to estimate precisely due to the heterogeneity of the landscape and the big number of controlling factors. Generally, the methods of obtaining ET are classified into three groups including direct measurement, modelling methods and Remote sensing methods. The overall objective of this study was to estimate spatial and temporal evapotranspiration for water resource assessment and management using remote sensing. Specifically, it sought to identify parameters for estimating evapotranspiration, select suitable remote sensing data for estimating evapotranspiration and finally estimate spatial and temporal evapotranspiration in Ndaka-ini Dam watershed between the years 2016-2019.The project utilized Surface Energy Balance system Model that requires emissivity, Land Surface Temperature, Albedo, Fractional Vegetation cover, Leaf Area Index (LAI), and Normalized Vegetation Difference Index (NDVI) inputs obtained from remote sensed images. Landsat 8 images of 30 metres resolution were found adequate for the study. The Maps showing spatial and temporal estimated values per Land-cover in Ndaka-ini watershed between the years 2016-2019 were obtained. The results showed that the Mean estimated ET values were 5.65, 4.67, 6.23 and 6.07mm/day for 2016, 2017, 2018 and 2019 respectively. These indicated that 2018 had the highest mean estimated ET which is an indication of more water availability in the catchment as compared to the other years. Spatio-temporal variations in ET for the different land cover results indicate that dense forest has the lowest mean ET of 5.39mm/day and Perennial cropland has the highest mean ET of 5.83 mm/day. This is a clear indication that some land covers like perennial cropland has greater water requirements that others. It was concluded the spatial and temporal distribution of estimated ET were mapped which is an advantage of this method over the direct measurements method. Remote sensing could hence be used to estimate ET at regional and global scales which can help in water accounting and planning.

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ACRONYMS

ASL	Above Sea Level
EMR	Reflected or Emitted Electromagnetic Radiation
ET	Evapotranspiration
FVC	Fractional Vegetation Cover
ILWIS	Integrated Land and Water Information System
LAI	Leaf Area Index
LST	Land Surface Temperature
METRIC	Mapping EvapoTranspiration at High Resolution with Internalized Calibration
MODIS	Moderate Resolution Imaging Spectroradiometer
NDVI	Normalized Difference Vegetation Index
SEBAL	Surface Energy Balance Algorithm for Land
SEBI	Surface Energy Balance Index
SEBS	Surface Energy Balance System
SLURP	Semi-distributed Land Use-based Runoff Processes
S-SEBI	Simplified Surface Energy Balance Index
SWAP	Soil, Water, Atmosphere and Plant
SWAT	Soil and Water Analysis Tool

CHAPTER 1: INTRODUCTION

1.1 Background

Water is a very important commodity for sustaining life and also a key factor in sustaining agricultural production, energy production and other activities at optimal levels. Despite water being very important, the world including Kenya is far from being water secure which is proven by the demand of water already surpassing supply in most regions. Most countries in the world including Kenya indicate a strong probability of future water scarcity. Transitioning towards sustainable and resilient societies pivots on accountable management of the limited natural resources; Land and water-based ecosystems and the rich biodiversity they support provide food, clean water and air, and raw materials that fuel economic growth and consequently support the big four agendas in Kenya. They also provide natural sites for human settlements and mitigate climate change.

The availability Water has already been acknowledged as a universal problem that requires constant assessment to support sustainable use. Assessing water availability is one aspect of water resources management that is of great and growing importance as the population of the earth increases, thereby placing greater stress on existing water supplies. The assessment of water resources of an area and its changes with time means the assessment of individual components of the water cycle which components are shown in figure 1.1. The quantification of these components involves estimating the amount of water stored in various environments in the hydrologic cycle. The water hydrological cycle constitutes of various components, including precipitation, runoff, storage and Evapotranspiration (ET) among others.

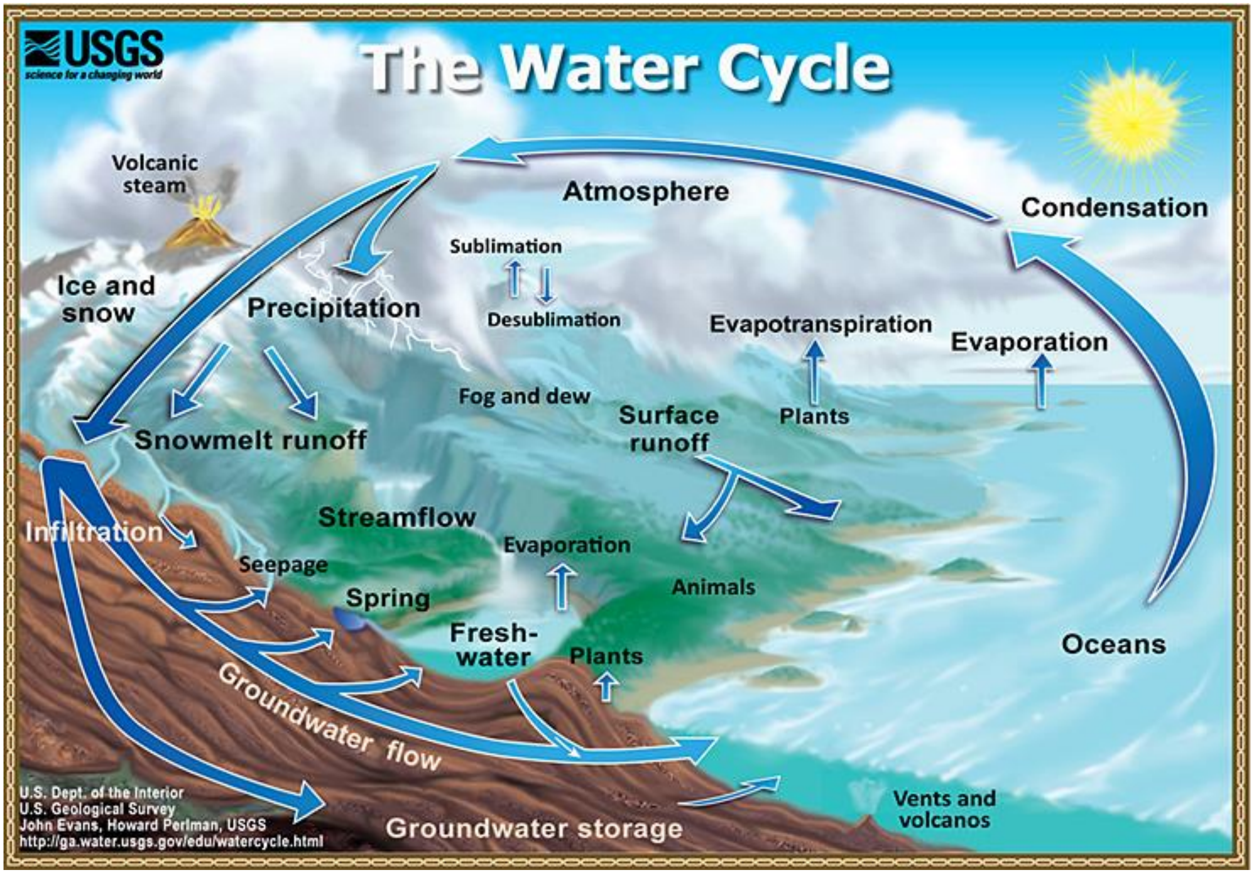


Figure 1.1: Components of the water cycle

Source: USGS, https://water.usgs.gov/edu/watercyclesummary.html

Evapotranspiration (ET) is one of the main components in a water cycle; second largest after precipitation (Maeda *et al.,* 2011). However, these two i.e. ET and precipitation are the most challenging constituents of the water hydrological cycle to estimate precisely due to various reasons that include the scenery heterogeneity and controlling factors involved, including Soil properties, topography, climate, and plant biophysics among others (Cosgrove *et al*., 2015).

ET data is regarded as one of the key factors in assisting water resource management. Previous research revealed that satellite earth observation data can provide a relatively timely and cost-effective means of acquiring spatially representative ET estimates, which are sought after by various water resource managers and planners. Some of these studies include (Shoko, 2014): (Gibson *et al*.(2013), (Hailegiorgis, 2006): (Cosgrove et al, 2015): (Ghanshyam *et al*. 2013) which were been carried out in The Netherlands, South Africa and India. Jarmain *et al*.(2009)

noted that estimating ET accurately has remained a big challenge to most researchers in many fields including water resources managers and planners.

As discussed by Gieske (2003), different methods for monitoring and estimating ET on global, regional and local scales have been developed. Some being more suitable than others in terms of the purpose for estimating, accuracy, total cost and data availability. However, it has been noted that the estimates obtained using ground based meteorological approaches are insufficient for representing large-scale spatial-temporal variations of ET. According to Shoko (2014) some methods are more suitable for a particular given space and time.

This research has used Remote sensing methods which have the capability to estimate *ET* across larger spatial extents, diverse land covers and through catchment boundaries. Satellite imagery such as Landsat 8 provides multi-temporal in addition to spatially explicit information from the earth' s surface on reflected or emitted electromagnetic radiation (Verstraeten *et al.,*2008), techniques to evaluate area ET using earth observation have been established for large expanses and at different spatial scales. Data in multiple landsat 8 EMR wavebands allow for the generation of the various inputs require for estimation of ET. These include land cover and vegetation cover, albedo, land surface temperature, emissivity and energy flux information. Data at regional and global scales permits for bigger spatial coverage than is probable with ground measurement methods (Melesse *et al*., 2006).

Ndaka-ini Dam Water has been reducing significantly and during the rainy seasons in 2018, it was increasing at very low rates (See plate 1.1). Because of these reasons there has been a rationing programme being implemented by the Nairobi Water and Sewerage Company since January 2017. Considering these problems, this research therefore sought to estimate the spatial and temporal variability of *ET* and subsequently make conclusions and recommendations that can help in water management.

Plate 1.1: Ndaka-ini dam showing low water levels in rainy season April 18, 2018,

Source: https://www.the-star.co.ke>2017/04/06

1.2 Problem Statement

Ndaka-ini dam has remained with low water levels over the last few years despite the heavy rains that caused havoc in almost in all parts of the country. In 2018, Meteorological reports indicated that the Aberdares region had received heavy rains but the dam was only half-full. In contrast, both Sasumwa and Ruiru dams which also depend on the same Aberdare water catchment, though being far smaller than Ndaka-ini dam, had attained maximum water levels. Residents living in the upper areas of Ndaka-ini indicated in 2018 that the four tributaries that feed Ndaka-ini dam have not attained maximum flows for the past three years. In turn, this has resulted in the long rationing programme being implemented by the Nairobi water and Sewerage Company since January 2017. Most estates get water once or twice a week. This information raises a lot of questions, hence the need to check the water cycle in the catchment area and hence know the sustainability of the dam. On the other hand, prevailing weather conditions in Kenya intensify Evapotranspiration and hence deplete the water availability; this makes the available water becomes scarce and hence consequently causes conflicts between the needs for environment, humans, wildlife, and agriculture.

In the past, measurement of the hydrologic components (Precipitation, Evapotranspiration, Runoff, Ground water and Interception and infiltration)was mainly accomplished by in-situ or point measurements demanding a dense network of in-situ observations which is expensive and demanding especially with constrained economic resources such as in Kenya. There exists a sparse network of these sites in Kenya. The ground-based measurements are normally point based and hence not practical over a large area. Lack of meteorological data from ground stations is a clear barrier to the proper management of water resources in poor countries, increasing the risks of water scarcity and water conflicts. Most water resources management problems are either local or regional in nature and hence need methods that can provide global or regional spatial extent data instead of point data, hence the proposal to use remote sensing methods.

1.3 Objectives

The overall objective of this study is to estimate Evapotranspiration (ET) for water resource management using remote sensing, in Ndaka-ini the Dam Watershed.

Specific Objectives:

1. To identify the parameters for estimating ET
2. To select suitable remote sensing data for estimating ET
3. To estimate spatial and temporal Evapotranspiration in Ndaka-ini Dam watershed / Catchment area between 2016-2019

1.4 Justification for the Study

Justification of the study is meant to highlight its significance in terms of who the users of the end results will be and how they will benefit. The study is significant because the result will show the status of the catchment area especially when internationally it is nowadays known that remote sensing methods have unlimited potential for estimation of spatial-temporal ET at both point and watershed scale. Data obtained by Satellite Earth observation techniques can be used in these ET estimation approaches to extend in-situ measurement of ET to much larger extents, including areas where meteorological measurements are scarce. Since the Ndaka-ini watershed is large and has a heterogeneous landscape with varying topography and vegetation characteristics, Remote sensing methods will be useful, effective and economical in the estimation of ET at a regional scale. Ndaka-ini dam problems need scientific research that assesses the water cycle and water use in the watershed and its sustainability. By looking at the water availability and use in the watershed through estimation of ET, it is possible for the water resource managers to check the sustainability of the dam and the ecosystem.

Both Baariu (2017) and Mumina *et al*. (2017) researched on drought effects on Ndaka-ini dam using remote sensing but the research didn’ t touch on Evapotranspiration. However they found out that there were some effects of drought on the Dam. In most of the studies done in this area, none has attempted to look at ET using remote sensing methods.

1.5 Scope of work

The research explores the assessment of Ndaka-ini watershed water resources using estimated Evapotranspiration by use of remote sensing methods. The research entails estimating *ET* values from satellite images acquired between 2016 and 2019.The research will help assessing the catchment area in terms of water availability.

Despite the many advantages of using remote sensing methods, the approach poses some short comings. Limitations include Absorption of radiation by the objects, unavailability of thermal infrared satellite imagery of high resolution which are crucial when estimating the energy fluxes, scattering caused by clouds

1.6 Organization of the report

The report is organized into five chapters:

Chapter one: contains the background, problem statement, justification, scope and organization of the report.

Chapter Two: Contains literature review of the Evapotranspiration theories and methods of estimation.

Chapter three: Gives detailed information on area of study, data used in the study and their sources plus all the methods that have been applied to achieve the results.

Chapter four: This provides the results obtained and discussion of the results.

Chapter five: This gives conclusions and recommendations based on the findings obtained from the study.

These are followed by References and two appendices.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction to Evapotranspiration (ET)

Evapotranspiration (ET) is the acronym for evaporation and transpiration; it includes plant leaf transpiration and evaporation from a variety of surfaces. These joint processes whereby loss of water from the soil surface through evaporation and from plants through transpiration occurs concomitantly and it is difficult to distinguish amid the two procedures. Evapotranspiration is a process of water moving from the Earth's surface to the atmosphere and is a vital component of natural water cycle. ET is more closely connected to water use and balance in a basin but it has not been used widely in the past because of poor parameterization and a general lack of calibration and validation data Accurate estimations of spatio-temporal variations in precipitation and Evapotranspiration (ET) are critical for better understanding of the interactions between land surfaces and the atmosphere (Cosgrove *et al*., 2015) and (Mu *et al*., 2007). According to Hailegiorgis (2006), the actual ET is an indicator of the water requirements for both crops and trees for achievement of healthy development and productivity.

Tghere are other factors that affect evapotranspiration in addition to water availability at the evaporating and transpiring surfaces. These factors comprise of temperature of the air, speed of the wind, solar radiation, air humidity, wind speed, vegetation type, vegetation density, rooting depth, and the characteristics of the land surface. Quantitative understanding of these parameters is of great importance in water balance in a catchment/basin in that:

1. They can give the difference between ET and precipitatioin which is interpreted as the available water for use in a long period of time.
2. In irrigated lands, information on ET assists in efficient use of water without loss.

2.2 Importance of ET estimation

The most substantial constituent of the hydrologic water budget Apart from precipitation is Evapotranspiration. Evapotranspiration changes with regions and seasons; during drought season, it varies according to wind and weather conditions. Because of these erraticism, water managers who are responsible for planning and arbitrating the distribution of water resources need to have a exhaustive knowledge of the Evapotranspiration process and knowledge about the spatial and temporal rates of Evapotranspiration. The reduction in ET means reduction of the real water consumption and it is assumed that as water becomes limiting, there is reduction in transpiration and therefore subsequently plant temperature increase.

The change in Evapotranspiration over a period of time can be utilized to evaluate the variation in availability of water in an area . These information can be of great use in studies concerning climate change, as well as in length and intensity of drought analysis. Understanding what is happening within a catchment area and conserving the ecosystem can save the catchment by increasing water availability and recharging the water table therein. Additionally, timely spatial and temporal mapping of the water cycle components provides vital information on the state of these water resources, the environment, development trends and also wildlife habitat.

2.3 Methods of estimating ET

Generally, the methods of obtaining ET can be classified into 3 groups which include:

1. Direct measurement methods
2. Modelling methods and
3. Remote sensing methods

2.3.1 Direct measurement methods

These methods are challenging and special equipment are required to measure soil water balance. These equipment are very expensive and rarely available and therefore ET estimates are regularly estimated from reference ET estimates. Shoko (2014) describes this as a technique used to estimate ET by accurately measuring water components in a natural environment. These water components include storage of soil moisture in the soil and deep drainage. Examples of indirect methods include Lysimeter, Bowen Ratio method and Eddy correlation method (Shoko, 2014).

2.3.2 Modelling method

This includes *water balance* and *hydrologic models*. According to Tsegaye (2015), the *water balance* approach primarily considers the amount of precipitation and the time-based distribution of rainfall in fulfilling the crop water demand (Reference ET) through soil moisture modelling. It encompasses applying the water balance equation to the area of interest over a specific period of time and consequently solving the equation. The method can estimate ET accurately if accurate information on the balance component is available.

Hydrological models: Hydrological surface flows such as SWAT,SWAP and SLURP simulate the transformation of precipitation into stream flow taking into account all the intermediate processes such as evapotranspiration, interception, infiltration, runoff and ground water flow and including all the artificial effects of dams, reservoirs, diversions and irrigation schemes. They are therefore able to model evapotranspiration at many points and at many times (Hailegiorgis, 2006).

2.3.3 Remote sensing method

Many researchers estimate spatial and temporal ET over large areas by use of surface energy balance method which utilizes remote sensing data. This is because spatial and temporal variations of ET cannot be achieved by use of point based methods. These methods entail the use of energy balance models and vegetation indices. Land surface temperature (LST) which can be derived from earth observation data drives the energy surface and is a more direct observation of the amount of water the crops evaporate and transpire. According to Senay *et al.*, (2013), healthy and well-watered vegetation and subsequently vegetation that transpire freely, has a much cooler surface temperatures than unhealthy and water-stressed vegetation. The energy surface model has an advantage that prior knowledge of the crop calendar is not needed. This crop calendar may indicate length of growing period, crop type, start and end of growing seasons etc). Also, the energy balance method does not require assumptions on optimum crop management as is the case with water balance models (Senay *et al.,* 2013). The method involves determining land surface variables that assist in estimating energy fluxes including albedo, emissivity and Normalized Difference Vegetation Index (NDVI). The LST offer all-inclusive parameter that takes into account the effects of diseases, water, pests, crop condition, and management practices among other factors.

The advent and development in remote sensing technology allows the spatial monitoring of total evapotranspiration over large extents. An opportunity to check and monitor spatial variations of total ET at diverse spatial and temporal scales is made possible the increased accessibility, availability and development of satellite data products (Glenn *et al.,* 2007); (Ruhoff *et al.,* 2012) and permits the monitoring of unreachable areas (Li *et al*., 2009). In addition, (Gibson *et al*. 2013) highlight that to be able to monitor water resources in comparatively large areas in a cost effective manner, utilization of remote sensing is key and it holds a great promise for the long-term plans. To be able to evaluate of spatial variations of total ET for long periods it can be pointed out that the methods that utilize earth observation data are more suitable. These methods include use of NDVI and the energy balance models, for example the Surface Energy Balance Algorithm for Land (SEBAL), the Simplified Surface Energy Balance Index (SSEBI), Surface Energy Balance Index (SEBI), the Surface Energy Balance System (SEBS), and Mapping Evapotranspiration at High Resolution with Internalized Calibration (METRIC). Since ET requires energy to occur, the energy balance models are all based on energy balance method (Shoko, 2014).

2.4 The Surface Energy Balance System (SEBS)

This model was developed by Prof Su in 2002. From earth observation or remote sensing data, It estimates heat energy fluxes. The remote sensing data which includes computation of NDVI, land surface temperature, emissivity, leaf area index albedo, fractional vegetation cover). In addition, meteorological data including air temperature, air humidity, air pressure and wind speed at a reference height are required. According to Su (2002) SEBS also needs solar radiation, which can be directly measured on the ground using meteorological methods or based on the energy balance equation, it can be modelled from remote sensing data. By calculating the energy required to transform water from liquid to gas the SEBS model estimates daily ET from remotely-sensed and meteorological data: It is computed as follows:

$\lambda E = R_n - G_0 - H$……………………………………………………….(Eqn 1)

Where:

λE is the turbulent latent heat flux (λ is the latent heat of vaporisation and E is water vapour flux density),

R_n is net radiation,

G_0 is the soil heat flux and

H is the sensible heat flux

The soil heat flux is derived indirectly, using empirical relationships between vegetation and land surface characteristics. Soil heat flux (G0) is the amount of heat energy flowing into a cross-sectional area of soil per unit of time in response to the temperature gradient. However, sensible and latent heat fluxes rely on the characteristics of the input image (to derive dry and wet limits) and also the bio-physical characteristics of the area under study (Li *et al*., 2009).

To derive the evaporative fraction, the relative evapotranspiration is used together with net radiation Rn, soil heat flux and the latent heat flux at the wet limit (Eqns. (2) and (3)).

$$\Lambda_r = 1 - \left\{ \frac{H - H_{wet}}{H_{dry} - H_{wet}} \right\} \text{.. Eqn 2}$$

Where:

Λ_r is relative evapotranspiration,

H is the sensible heat flux and

H_{wet} and H_{dry} are the sensible heat flux at the wet and dry limits, respectively.

$$\Lambda = \frac{\lambda E}{R_n - G_0} = \frac{\Lambda_r \,.\, \lambda E_{wet}}{R_n - G_0} \text{ ....Eqn 3}$$

Where:

Λ is the evaporative fraction

λE is the latent heat flux and

λE_{wet} is the latent heat flux at the wet limit.

In SEBS it is assumed that the daily value of evaporative fraction is approximately equal to the instantaneous value, and, from this, the daily evapotranspiration can be determined as:

$$ET = 8.64 * 10^7 \; * \frac{\Lambda - \overline{R}_n}{\lambda \rho_w} \text{ ....Eqn 4}$$

Where:

ET is the estimated evapotranspiration on daily basis (mm per day)

λ is the latent heat of vaporization (Joules per kg)

ρ_w is the density of water (kg per cubic metres)

Rn is the daily net radiation flux

8.64 x 107 is the constant used to convert instant ET to daily ET

To estimate the latent heat (λE) and the sensible heat(H)fluxes, SEBS uses the Monin-Obukhov Similarity Theory (MOST).A detailed explanation of how MOST relates surface fluxes to surface variables and variables in the Atmospheric Surface Layer (ASL) is given Su (2002). SEBS has several advantages over other energy balance models; it calculates the aerodynamic resistance of heat transfer more explicitly instead of using fixed values, unlike other models like SEBI and SEBAL, (Li *et al.*, 2009). The aerodynamic resistance is very important when estimating ET using remote sensing methods as highlighted by Liu *et al*. (2006). Aerodynamic resistance for different surface types varies with variations in environmental conditions hence it has an impact on the estimation of heat fluxes, and subsequently, on total ET (Sugita and Kishii, 2002).

In addition, SEBS is free of charge and is embeded into the open source freeware Integrated Land and Water Information System (ILWIS) package available free of charge from (http://www.52north.org) on the other hand, SEBAL, which is protected by intellectual property (Gibson *et al.*, 2013). Using different remote sensing approaches, SEBS has been used internationally to estimate total evaporation for different land cover types and it has been acknowledged that it yields reliable estimates.

This research will utilize the remote sensing SEBS model; The SEBS model is freely available and it can be used by practitioners with remote sensing knowledge who may not necessarily have the micrometeorological expertise to come up with a model themselves. However, the derivation of ET using the SEBS model is a complex process that requires a numerous processing steps to derive transitional output remote sensing products.

Some of the SEBS (Surface Energy Balance System) MODEL inputs include the following:

- Meteorological inputs values
- Radiation inputs values
- Satellite data inputs files
    - Albedo
    - FVC
    - Emissivity
    - NDVI
    - Leaf Area Index (LAI)
    - Brightness temperature
    - Land surface Temperature

    - Julian day from metadata file
    - Sun zenith angle
- Land use parameters inputs
    - Land use land cover data
- Digital Elevation Model

2.5 Evapotranspiration Units

The Standard unit of measuring ET is millimetre per day (mm day^{-1}). Others that can be used include:

- M^3 per hectare per day
- Litre per second per hectare
- Equivalent radiation in mega joules per square metre per day

2.6 Reference Evapotranspiration

Reference Evapotranspiration is the rate of ET where there is no shortage of water in the soil for use by the crops. This is usually computed using meteorological data and formulae defined by various scholars, for example Penman Monteith, Hargreaves, and Samani.

CHAPTER 3: MATERIALS AND METHODS

3.1 Area of study

The research focused on the Ndaka-ini Dam watershed which is situated within Murang’ a County in Central Kenya. The county has a total area of 2,559 KM^2. The watershed hosts Ndaka-ini Dam which draws from three rivers namely Maragua, Gikie, and Irati, with their source being the Aberdare ranges and draining into the great River Tana. The area lies between latitudes 0º33'30" and 1º5'20" S, and longitudes 36º41'00" and 37º25'20" E. Ndaka-ini Dam is the primary source of water for the capital city of Kenya, Nairobi and its environs. The watershed’ s highest point is approximately 3,353m above sea level and experiences extremely distributed topography which is drained by numerous rivers. Tea is the main cash crop within the watershed and soils are mainly volcanic thus highly productive and significant for agricultural activities.

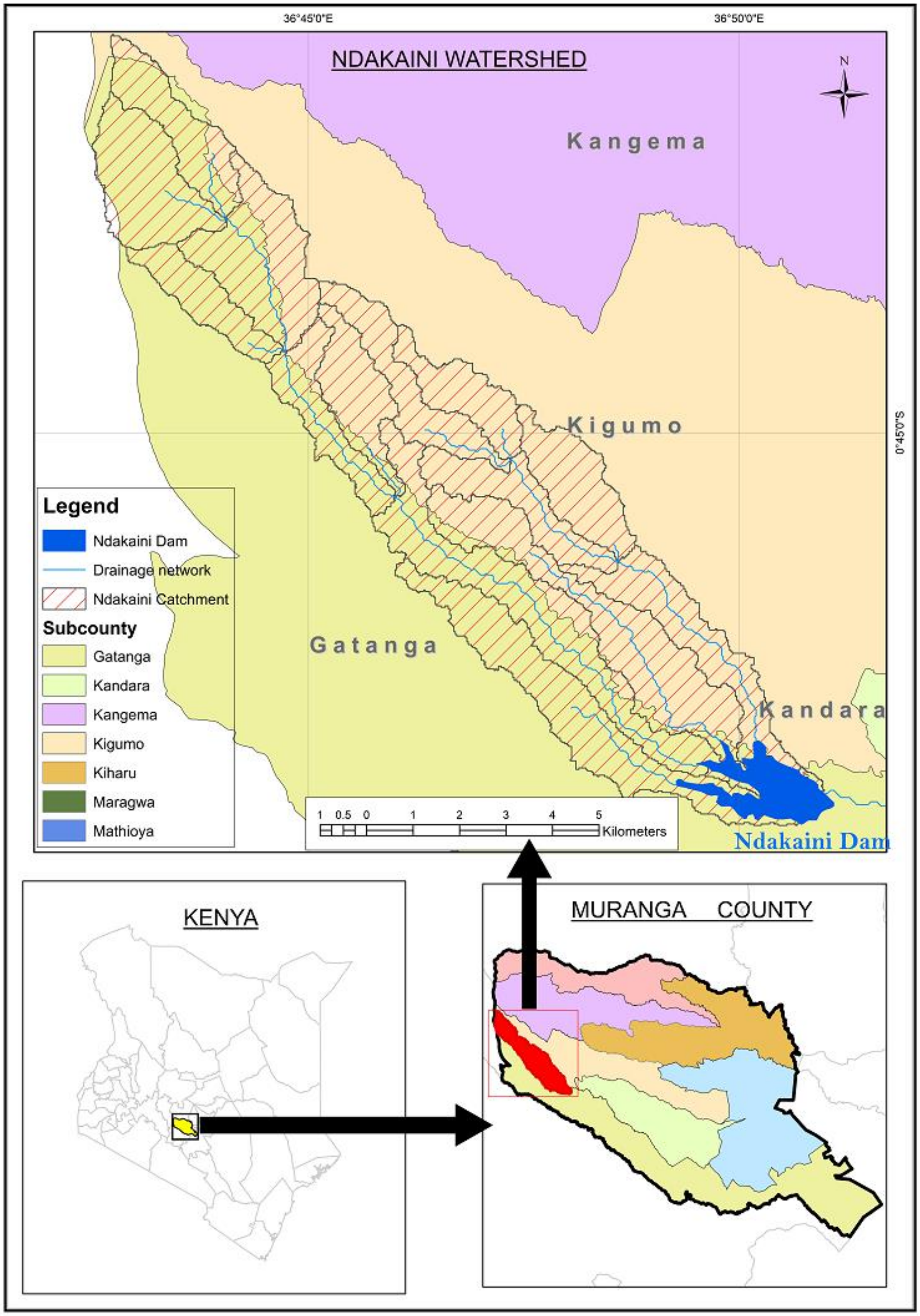

36°45'0"E
36°50'0"E
NDAKAINI WATERSHED
N
Kangema
Kigumo
0°45'0"S
Gatanga
Kandara
Ndakaini Dam
Legend
Ndakaini Dam
Drainage network
Ndakaini Catchment
Subcounty
Gatanga
Kandara
Kangema
Kigumo
Kiharu
Maragwa
Mathioya
1 0.5 0 1 2 3 4 5
Kilometers
KENYA
MURANGA COUNTY

Figure 3.1: Area of Study Map

3.2 SEBS Model Parameters, Data and Sources

The data identified relied on the parameters which were to be extracted. The data identified was as shown in Table 3.1.

Table 3.1: SEBS Model parameters, datasets obtained and their sources

Parameter	**DATA**	**SOURCE**
– Albedo – Emissivity – NDVI – Leaf Area Index – Brightness Temperature – Land surface Temperature – Julian day from metadata – Sun zenith angle – Fractional Vegetation Cover (FVC)	Landsat 8 Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS)	USGS https://earthexplorer.usgs.gov/
Meteorological Parameters	Wind speed, Air temperature, Humidity, Air pressure, Solar radiation, Precipitation	Kenya Meteorological Department
Digital Elevation Model	SRTM Digital Elevation Model	USGS https://earthexplorer.usgs.gov/
Land use/ land cover	Land use/ land cover	RCMRD
Auxiliary data	Roads,	Kenya Roads Board
	Administrative boundaries	IEBC

a) Landsat 8 Operational Land Imager and Thermal Infrared Sensor

Landsat 8 Operational Land Imager and Thermal Infrared Sensor were acquired from USGS website and used to estimate ET. Four images covering Ndaka-ini dam Watershed for four different years 2016, 2017, 2018 and 2019 were obtained. The Landsat datasets were carefully selected ensuring no or very minimal cloud cover. Mainly, the available Images were for the months of January and February when there is usually less cloud cover. Nine bands 1-7, 10 and 11 with wavelengths as shown in Table 3.2 were utilized for this study.

Table 3.2: Landsat 8 bands and wavelengths

Landsat 8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS)			
Band Number	**Band Name**	**Wavelength (µ)**	**Resolution (Meters)**
1	Coastal Aerosol	0.43-0.45	30
2	Blue	0.45 – 0.51	30
3	Red	0.53 – 0.59	30
4	Green	0.64 – 0.67	30
5	Near Infrared	0.85 – 0.88	30
6	SWIR 1	1.57 – 1.65	30
7	SWIR 2	2.11 – 2.29	30
8	Panchromatic	0.50 – 0.68	30
9	Cirrus	1.36 – 1.38	30
10	Thermal Infrared (TIRS) 1	10.60 – 11.19	100 (Resampled to 30)
11	Thermal Infrared (TIRS) 2	11.50 – 12.51	100 (Resampled to 30)

Source: USGS, 2019

b) Meteorological data

Meteorological data was obtained from Department of Meteorology, Nairobi. The data provided was for Thika Agromet station which is the nearest meteorological station to the area of study. The data covered years 2016 to 2018 as shown in Table 3.3. Data for the year 2019 was not availed.

Table 3.3: 2016 – 2018 Meteorological data for Thika Agromet station

Year	**Temperature**	**Rainfall**	**Wind speed**	**Relative Humidity**	**Solar radiation**
2016	12.65-28.72	15.1	3.2	49	19.34
2017	12.85-29.32	0	4.7	46	25.37
2018	10.70-28.00	0	4.7	40	25.72
2019	Not available				

c) Digital Elevation Model

The Digital elevation model data shown in Figure 3.2 was downloaded from http://srtm.csi.cgiar.org. The dataset was at a resolution of 90m and it was later resampled to 30m so as to be in line with other datasets.

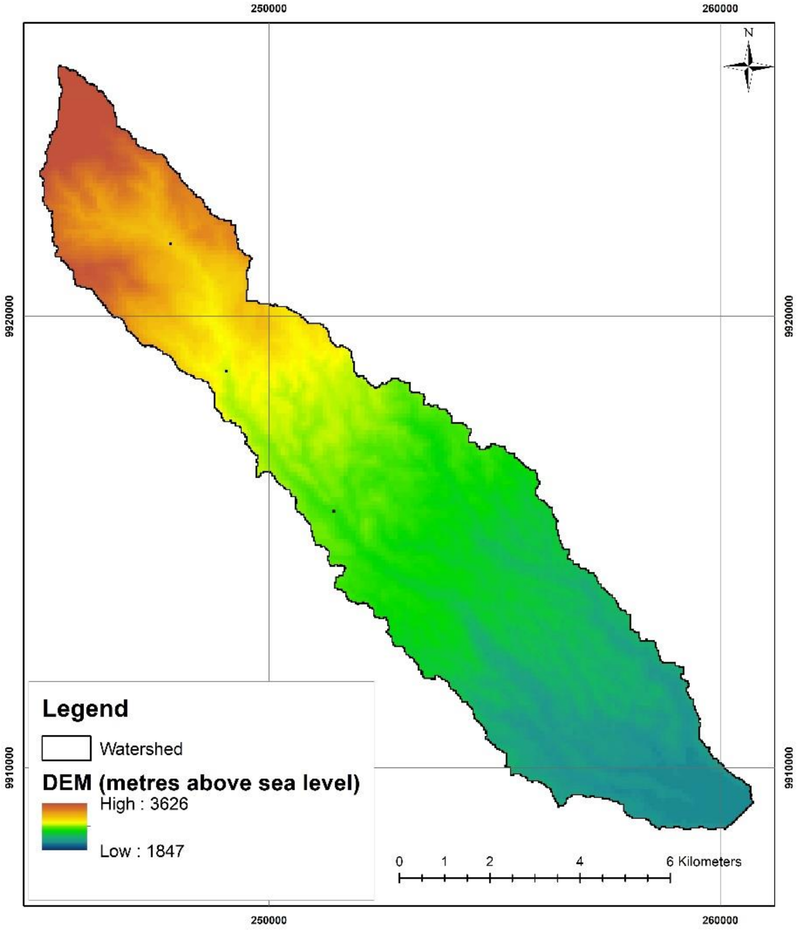


Figure 3.2: Ndaka-ini Dam watershed DEM

d) Land cover

This was obtained from RCMRD (Figure 4.6) plus its validation results which indicated an overall accuracy of 75%. The accuracy report is shown in appendix 1.

3.3 Methodology

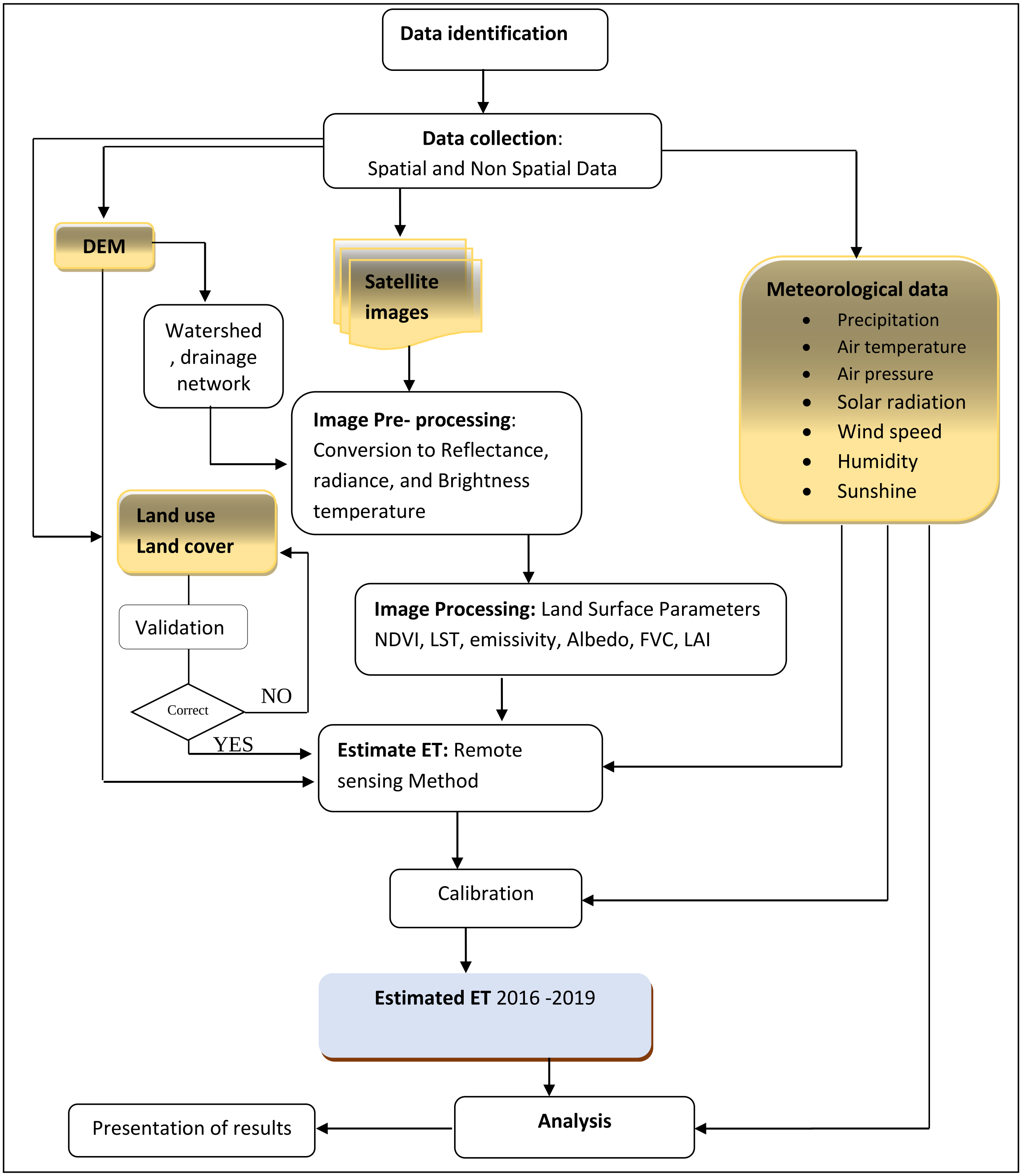


Figure 3.3 : Overview of methodology

3.3.1 Data Pre-processing

a. Extracting Area of Study

Using ArcGIS software, all the datasets were clipped using Ndaka-ini Dam watershed so as to obtain the area of study.

b. Conversion to Top of the Atmosphere (TOA) Spectral Radiance

Map Algebra tool in ArcGIS software was used to pre-process the Landsat images. Landsat 8 band 10 and 11 were converted into Top of the Atmosphere (TOA) Spectral radiance using the radiance rescaling factors that were obtained from Landsat Metadata File shown in Appendix 2. The formulae for this conversion is as shown in eqn 5.

$L_\lambda = M_L Q_{cal} + A_L$…………………………………………eqn 5

Where;

L_λ	-	TOA Spectral Radiance
M_L	-	Band specific multiplicative rescaling factor named RADIANCE_MULTI_BAND_x in the Landsat metadata file.Where x is the band number.
Q_{cal}	-	Quantized and calibrated standard product pixel values (DN)
A_L	-	Band specific Additive rescaling factor named RADIANCE_ADD_BAND_x in the Landsat metadata file. Where x is the image band number.

c. Conversion to Top of the Atmosphere (TOA) planetary Reflectance

Reflective bands Digital Numbers (DN) were converted into Top of the Atmosphere Reflectance using the rescaling coefficients provided in the Landsat metadata file. Eqn 6 was used to do these conversions for band 1 – 7. This was also done using map algebra tool in ArcGIS software.

$p\lambda' = M_p Q_{cal} + A_p$…………………………………………eqn 6

Where;

p_λ' - TOA planetary reflectance

M_p - Band specific multiplicative rescaling factor named REFLECTANCE_MULTI_BAND_x in the Landsat metadata file. Where x is the band number.

Q_{cal} - Quantized and calibrated standard product pixel values (DN)

A_p - Band specific Additive rescaling factor named REFLECTANCE _ADD_BAND_x. Where x is the image band number.

d. Correction for sun angle

The reflective TOA bands were also subjected to correction for sun angle was carried out using eqn 7.

$p_\lambda = p_\lambda' \ / \ \mathrm{Sin}(\theta * \pi /180)$………………………………………eqn 7

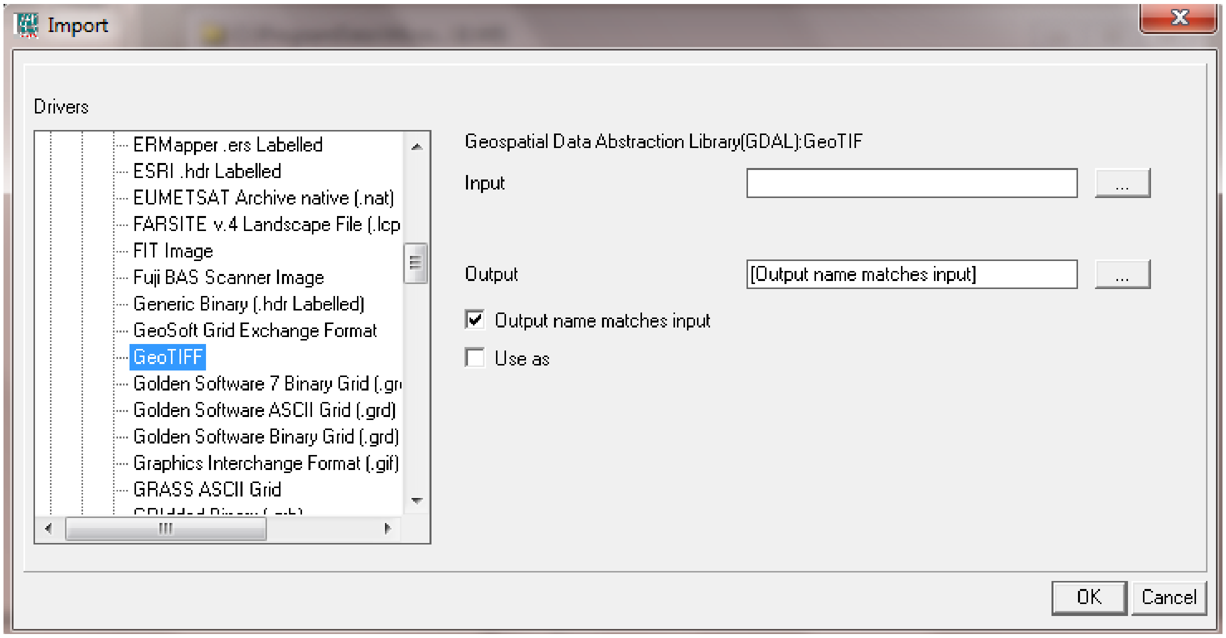
Where;

p_λ - Corrected Reflectance band

θ - is the Sun elevation is also obtained from Landsat metadata file.

e. Importing the Processed data into ILWIS

After pre-processing and processing of the data, the obtained inputs were all in Geotiff format. They were imported into ILWIS format using ILWIS software.



Geospatial Data Abstraction Library(GDAL):GeoTIF

Output [Output name matches input]

☑ Output name matches input

☐ Use as

Plate 3.1: Importing data into ILWIS

3.3.2 SEBS Remote sensing inputs

These inputs were derived from Landsat 8 images with a 30m resolution. These inputs include emissivity, Land Surface Temperature, Albedo, Fractional Vegetation cover, Leaf area index (LAI), and Normalized Vegetation Difference Index (NDVI). The inputs were retrieved from the formulae indicated in Figure 3.4.

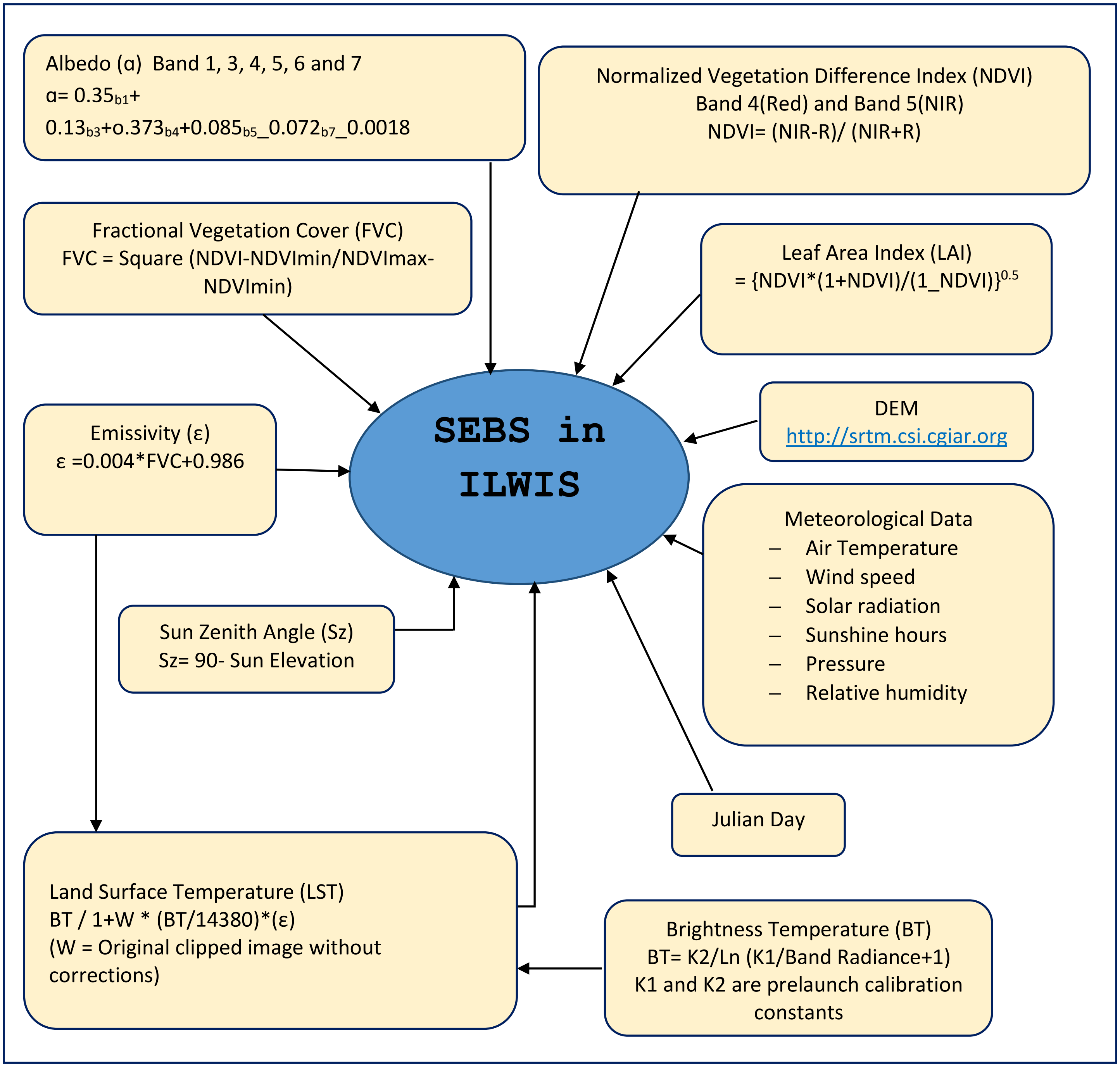


Figure 3.4: SEBS Model Inputs and derivation formulae

3.3.3 Estimating Reference ET from Meteorological data

The reference ET was computed using Hargreaves and Samani's formulae (equations 8-12) which is a temperature based method. The Microsoft office excel package was used to carry out the Reference ET calculations Using the following formulae.

$ET_O=1.25*0.0023*R\alpha T_r^{0.5}(T\alpha+17.8)$……………………………………………eqn 8

Where;

ET_O - Reference ET

$R\alpha$ - Extra-terrestrial Radiation (mm)

T_r - Temperature Range (Temperature maximum- Temperature minimum)

$T\alpha$ - Daily or Monthly Average Temperature

$R\alpha = 14.9158(h.\ \mathrm{Sin}\ \phi.\ \mathrm{Sin}\ \delta + \mathrm{Cos}\ \phi.\ \mathrm{Cos}\ \delta.\ \mathrm{Sin}\ h)\ r^2$………………………………..eqn 9

Where;

r - $1+0.17\ \mathrm{Cos}\ (0.017(186-Dj)$…………………..………….....eqn 10

ϕ - Latitudinal location in radians

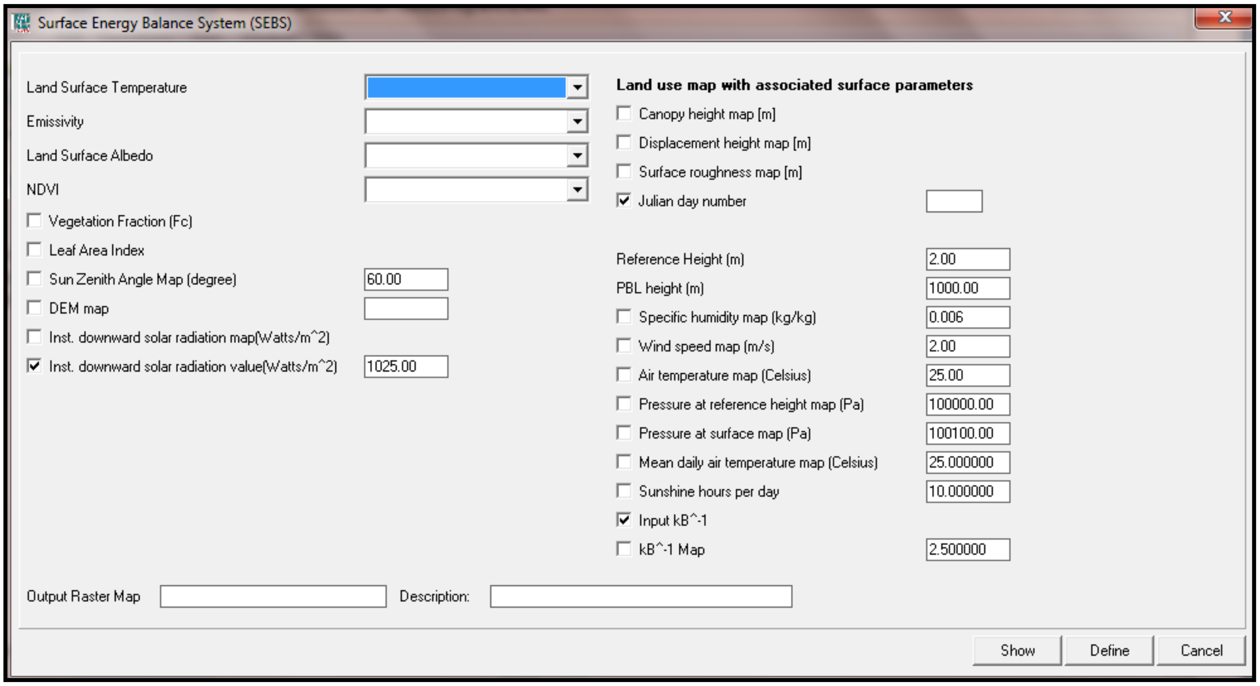
δ - Declination of the sun = $0.409\ \mathrm{Cos}\ (0.017(173- Dj)$..…..........eqn 11

h - $\mathrm{arccos}(\mathrm{Tan}\ \phi.\mathrm{Tan}\ \delta)$…………………………..............…....eqn 12

Dj - Julian Day

3.3.5 Estimating ET using Remote Sensing

The SEBS model is embedded into ILWIS software and therefore the process entailed inserting the relevant inputs into the SEBS template shown in Plate 3.2.



Land Surface Temperature
Emissivity
Land Surface Albedo
NDVI
☐ Vegetation Fraction (Fc)
☐ Leaf Area Index
☐ Sun Zenith Angle Map (degree) 60.00
☐ DEM map
☐ Inst. downward solar radiation map(Watts/m^2)
☑ Inst. downward solar radiation value(Watts/m^2) 1025.00

Land use map with associated surface parameters
☐ Canopy height map [m]
☐ Displacement height map [m]
☐ Surface roughness map [m]
☑ Julian day number
Reference Height (m) 2.00
PBL height (m) 1000.00
☐ Specific humidity map (kg/kg) 0.006
☐ Wind speed map (m/s) 2.00
☐ Air temperature map (Celsius) 25.00
☐ Pressure at reference height map (Pa) 100000.00
☐ Pressure at surface map (Pa) 100100.00
☐ Mean daily air temperature map (Celsius) 25.000000
☐ Sunshine hours per day 10.000000
☑ Input kB^-1
☐ kB^-1 Map 2.500000

Output Raster Map
Description:

Plate 3.2: SEBS model interface in ILWIS

3.3.6 Statistical Analysis

Validation for the estimated ET was important so as to give an insight on the performance of the remote sensing method used. Reference ET computed from meteorological data for specific dates when the satellite images were acquired was compared with estimated ET Obtained using remote sensing method. A paired T-test data analysis tool in Microsoft excel was used to determine whether they were significantly different.

Also, zonal statistics module in ArcGIS software was used to derive mean estimated ET for the various land covers in the watershed.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Results

In line with the objectives, the following results were obtained:

4.1.1 SEBS derived parameters/Inputs

The remote sensing SEBS parameters that were derived for purposes of estimating ET included:

a) Land Surface Temperature

The temperature values were given in Degrees Kelvin.

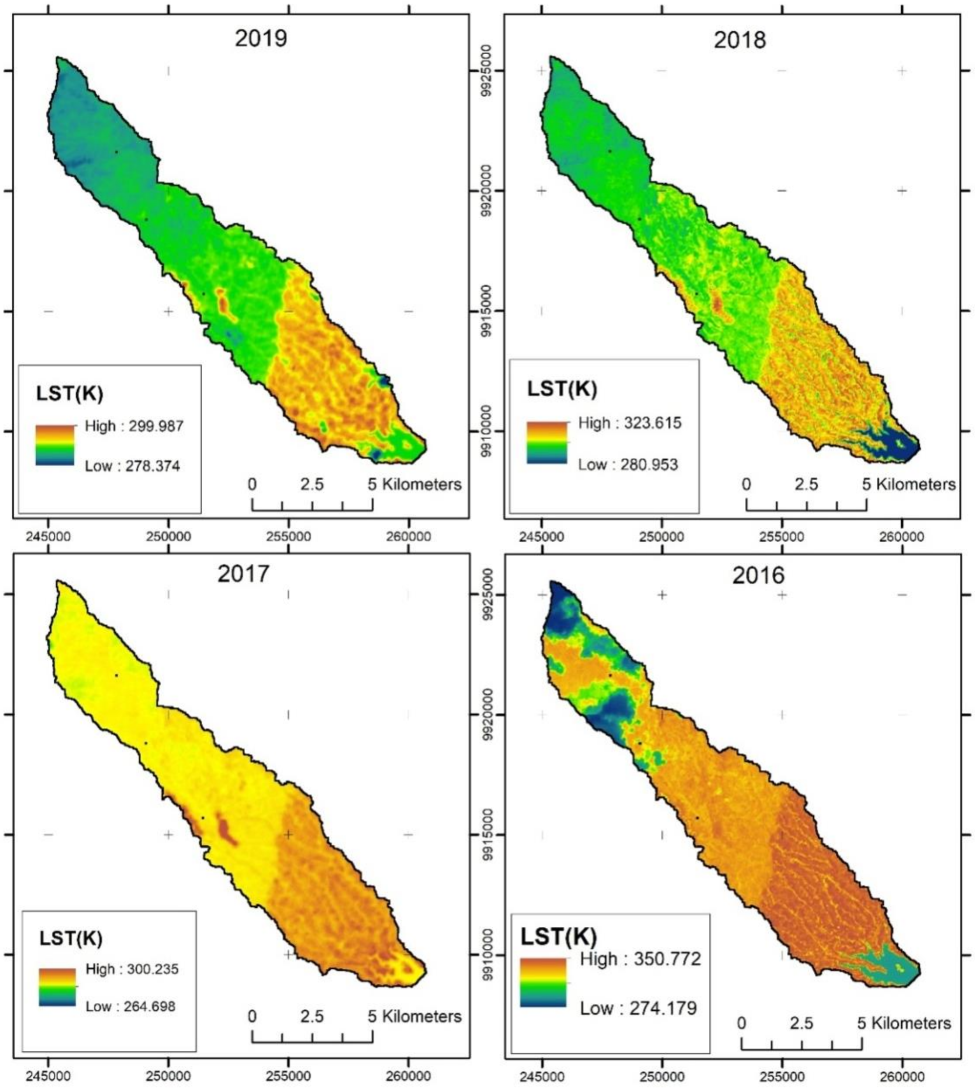


Figure 4.1: Land surface Temperature for Ndaka-ini Dam watershed between 2016 and 2019

b) NDVI

Normalized vegetation difference Index maps shown in Figure 4.2.

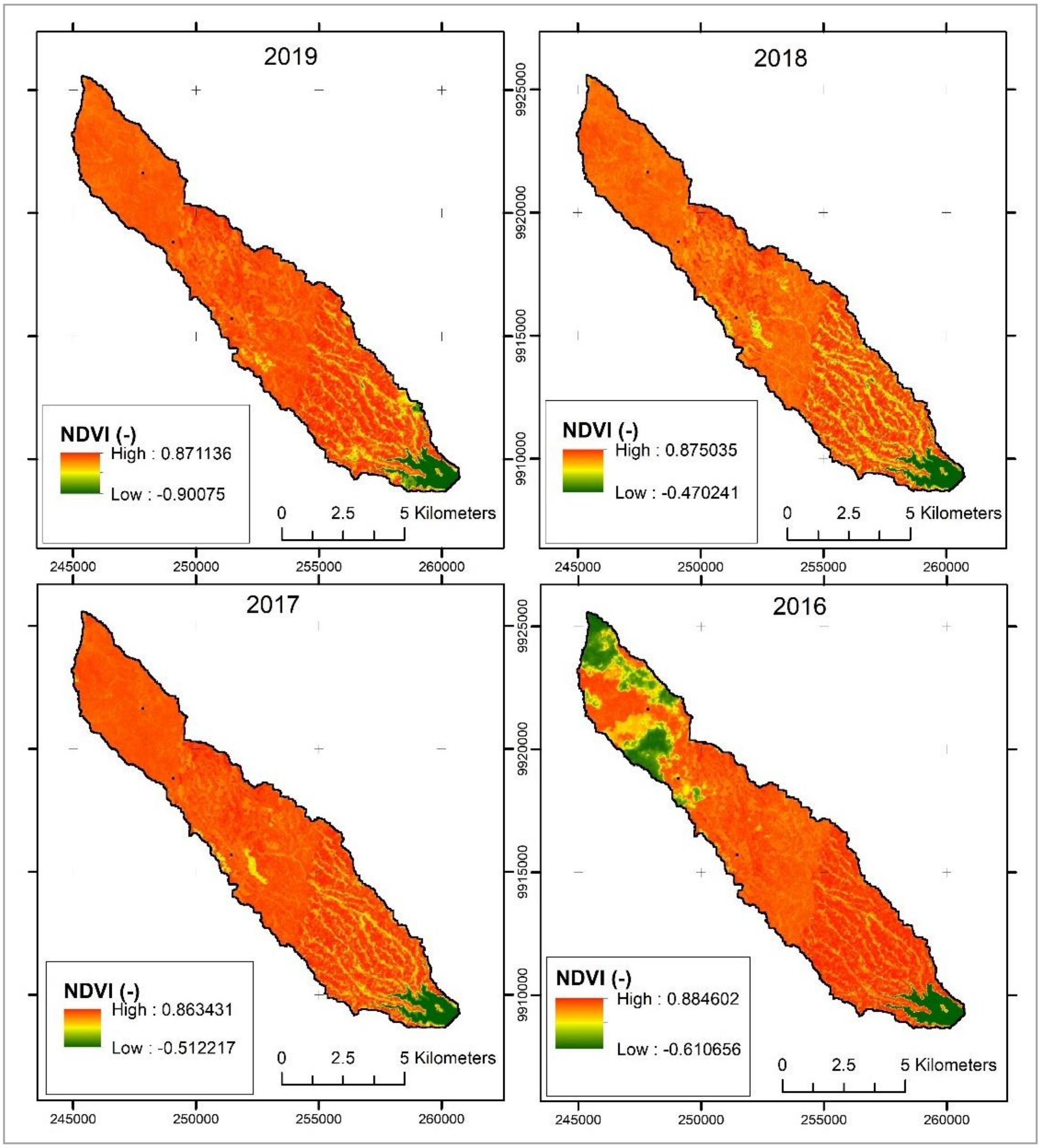


Figure 4.2: NDVI map for Ndaka-ini Dam watershed between 2016 and 2019

c) Albedo

Albedo maps for Ndaka-ini Dam watershed in shown Figure 4.3. These maps show the amount of radiation reflected by the surface

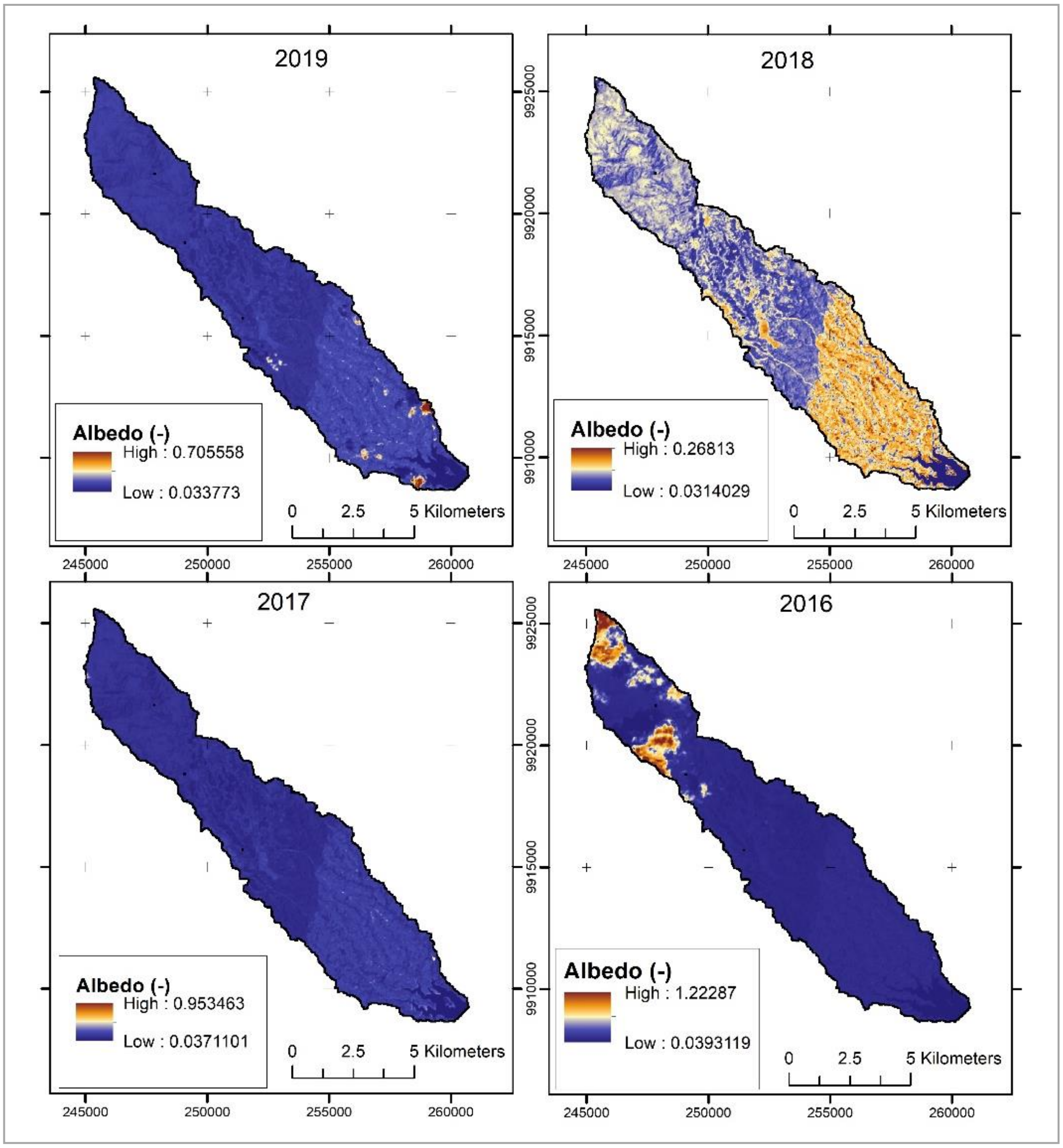


Figure 4.3: Albedo maps for Ndaka-ini Dam watershed between 2016 and 2019

c) Emissivity

Emissivity maps for Ndaka-ini Dam watershed in shown Figure 4.4. These maps show the amount of radiation emmited by the surface.

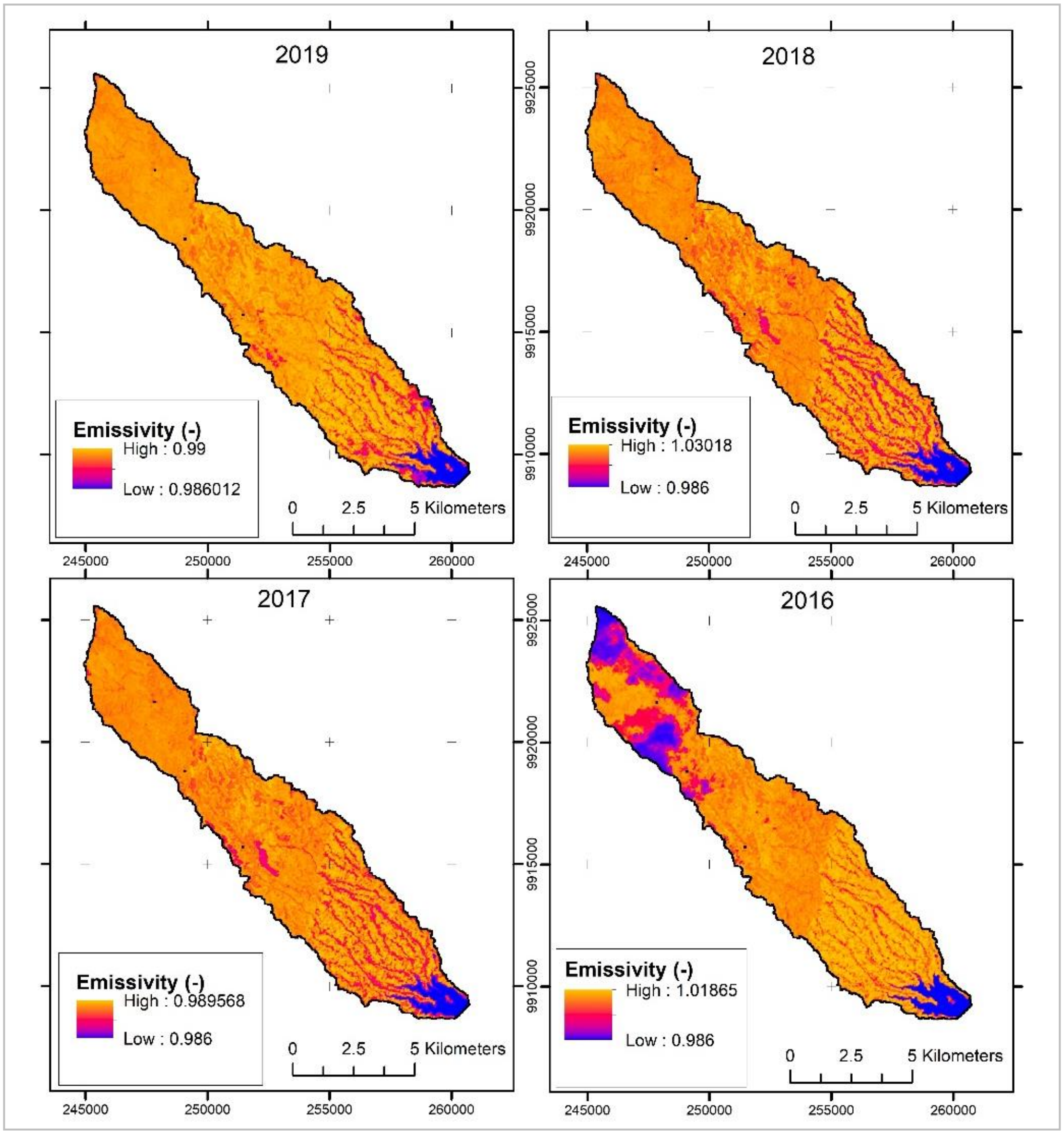


Figure 4.4: Emissivity maps for Ndaka-ini Dam watershed between 2016 and 2019

d) FVC

Fractional vegetation maps shown in Figure 4.5.

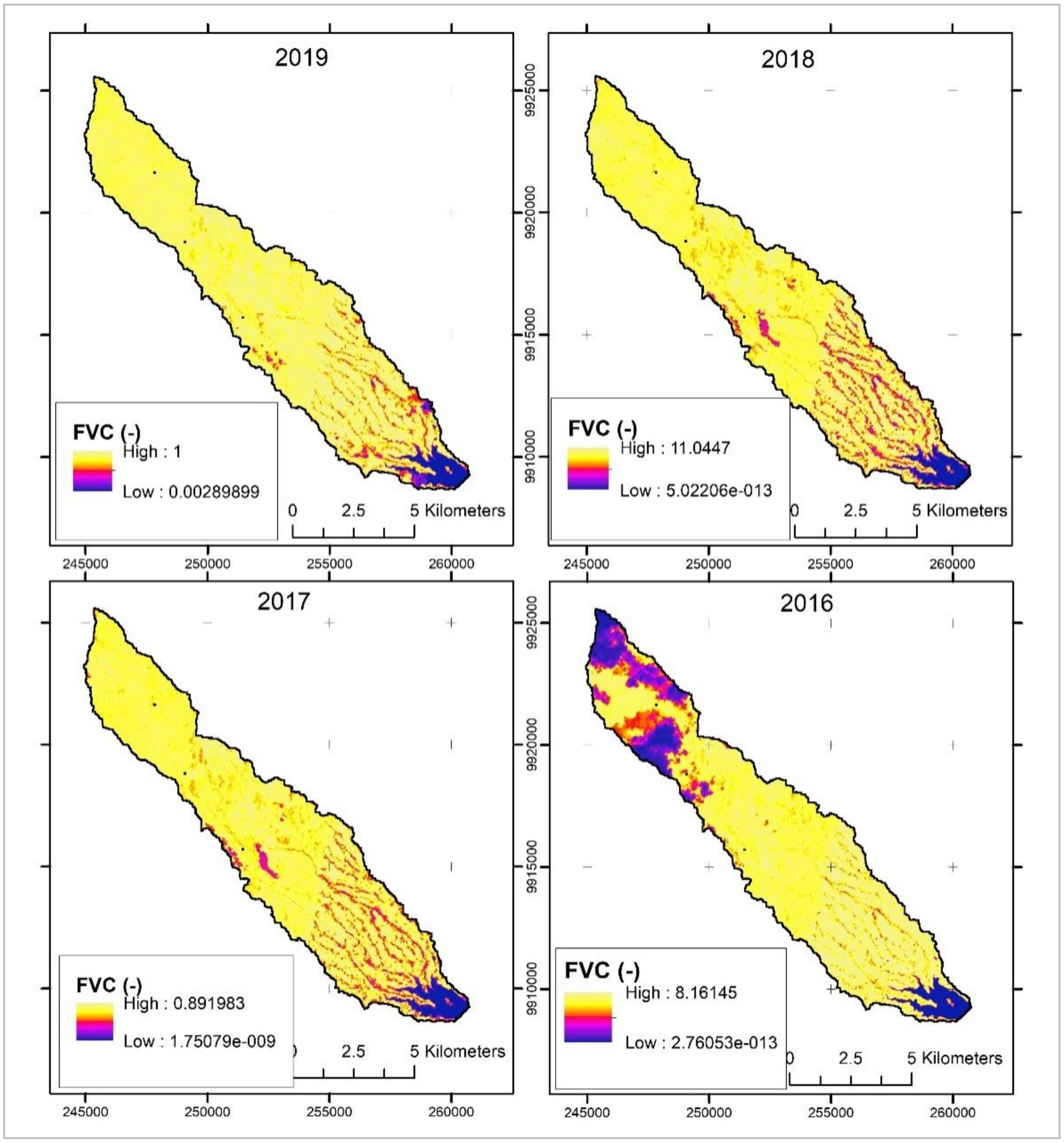


Figure 4.5: Fractional Vegetation Cover maps for Ndaka-ini Dam watershed between 2016 and 2019

4.1.2 Reference ET from Meteorological data

Computed reference ET values coinciding with the specific dates when the Landsat 8 acquisition dated were computed using meteorological data and they are shown in Table 4.1. Data for 2019 was not available.

Table 4.1: Computed Reference ET for 2016- 2018

Dates	**Computed Reference ET (mm/day)**
24-01-2016	6.60
26-01-2017	6.57
29-01-2018	6.71
01-02-2019	-

4.1.3 Land cover types and distribution within Ndaka-ini Watershed

The different land cover types that exist in the watershed are shown in Figure 4.6. The land cover types, acreages and their percentage cover are shown in Table 4.2

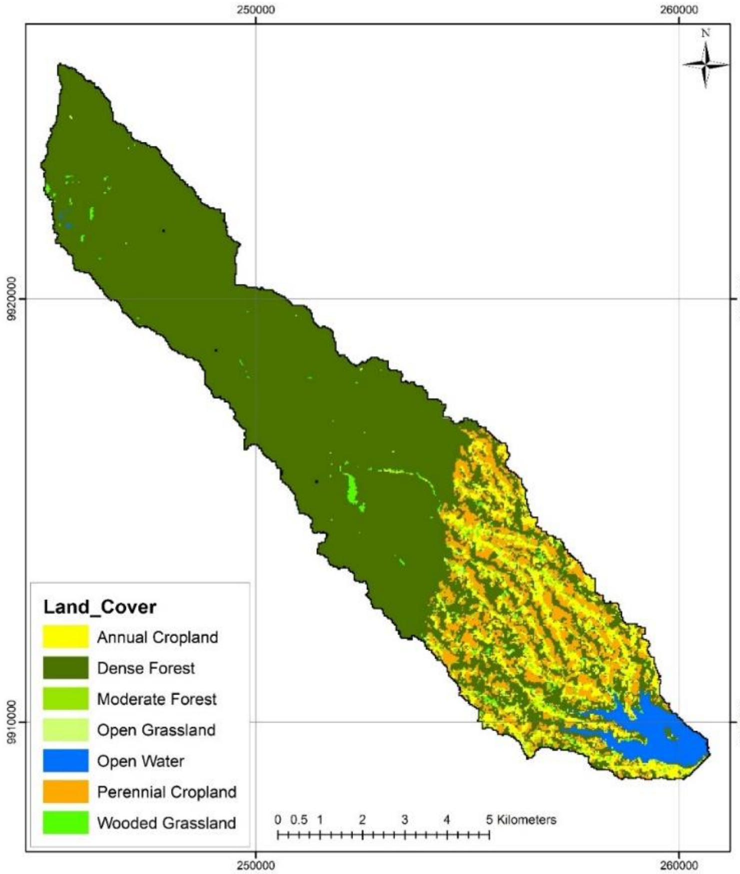


Figure 4.6: Main land cover types within Ndaka-ini Dam watershed,

Source: RCMRD, (FAO 2014)

Table 4. 2: Land cover types, acreage and their percentage cover in the study area

Land Use / Land Cover	**AREA (Ha)**	**% cover**
Annual Cropland	647.46	9
Dense Forest	5300.82	74
Moderate Forest	1.35	<1
Open Grassland	27.18	<1
Open Water	248.58	3
Perennial Cropland	756.18	11
Wooded Grassland	157.77	2

4.1.4 Estimated ET from remote sensing

The Spatio-temporal variations of estimate ET across Ndaka-ini Dam watershed for the periods 2016-2019 are ass shown in Figure 4.7.

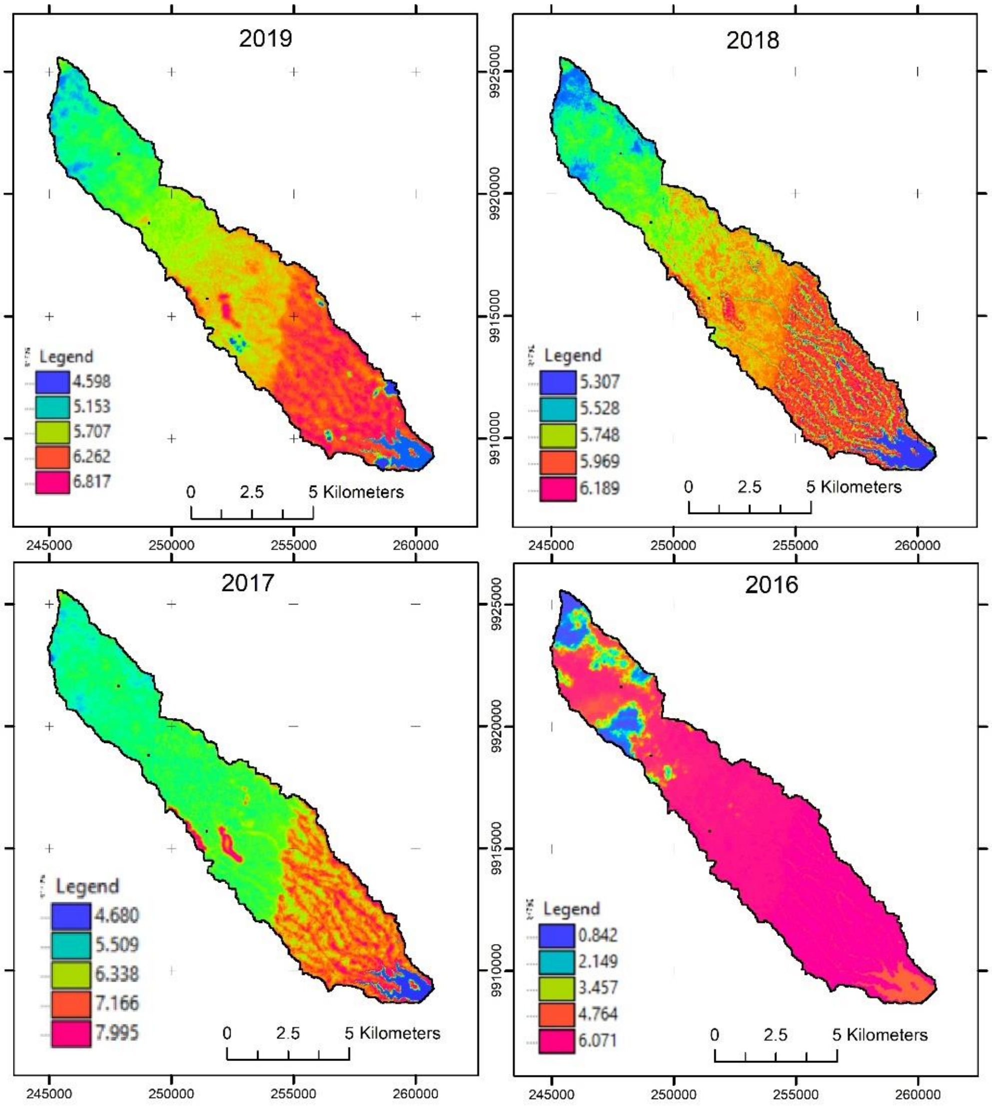


Figure 4.7: Spatio-temporal variations in ET maps (mm/day) for Ndaka-ini Dam Watershed between 2016 and 2019

4.1.5 Validation results

Comparison between Reference ET obtained from meteorological data and mean estimated ET from remote sensing shown in Table 4.3 was done using a paired T-test .The comparison results obtained are shown in Table 4.4. Meteorological data for 2019 was not available and hence Reference ET for the same year was not computed. For validation purposes, 2019 was omitted since it was missing Reference ET.

Table 4.3: Reference ET and mean estimated ET for 2016 - 2019

YEAR	**Ref ET(**mm/day)	**Mean Estimated ET (**mm/day)
2016	6.60	5.65
2017	6.57	4.67
2018	6.71	6.23
2019	_	6.07

t-Test: Paired Two Sample for Means		
	Variable 1	***Variable 2***
Mean	6.626667	5.516667
Variance	0.005433	0.621733

Table 4.4: Comparison results

Observations	3	3
Pearson Correlation	0.893534	
Hypothesized Mean Difference	0	
df	2	
t Stat	2.657714	
P(T<=t) one-tail	**0.058601**	
t Critical one-tail	2.919986	
P(T<=t) two-tail	**0.117201**	
t Critical two-tail	4.302653	

4.1.6 Spatial and temporal Variations in ET for Different Land covers

The spatio-temporal variations in ET for the different land covers are shown in Table 4.5 and Figure 4.8.

Table 4.5: Mean Estimated ET (mm/day) for the different land covers

Land Cover	**Estimated ET 2016**	**Estimated ET 2017**	**Estimated ET 2018**	**Estimated ET 2019**	**MEAN**
Wooded Grassland	5.79	4.70	6.41	6.18	5.77
Open Grassland	5.81	4.70	6.42	6.24	5.79
Annual Cropland	5.83	4.72	6.39	6.18	5.78
Dense Forest	5.09	4.43	5.79	5.71	5.26
Open Water	5.30	4.77	5.82	5.68	5.39
Perennial Cropland	5.89	4.71	6.45	6.26	5.83
Moderate Forest	5.73	4.69	6.38	6.02	5.70
Other land	5.73	4.77	6.20	6.26	5.74

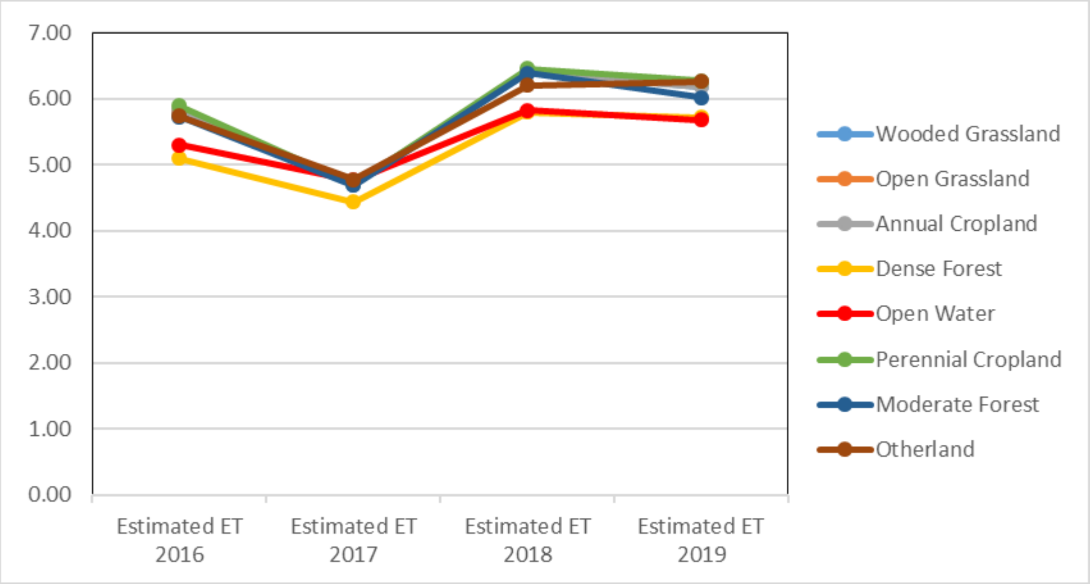


Figure 4.8: Graph showing Variations in ET for the different land covers

4.2 Discussion

From the LST results, Ndaka-ini Dam watershed showed variations in land surface temperatures over the four years of study. The western side part of the watershed depicts variations in LST over the four years, 2016 and 2017 having the highest values. Water body also shows some LST variations over the four years. Cropland which is on the eastern part of the study area generally had the highest LST over the four years.

The dominant land cover type in the study area is dense forest that covers 75 percent of the total area, followed by perennial and annual cropland with 11 and 9 percent cover. Open water occupies 3 percent of the total area.

Mean estimated ET values were calculated as 5.65, 4.67, 6.23 and6.07 (mm/day) for 2016, 2017,2018 and 2019 respectively. These indicate that 2018 had the highest mean estimated ET which is an indication of more water availability in the catchment as compared to the other years. Results from the spatio-temporal ET maps generally show high ET values on the eastern part of the study area and low values on the western side of the study area. The open water depicted relatively low values of ET across the four years. Variations in land cover affect ET which is demonstrated by the fact that Dense forest and water bodies have low estimated ET while annual and perennial cropland have higher values. This shows that the rate of ET is majorly controlled by the type of land cover and water availability.

Validation results show that P(T<t) two tail is greater than 0.05 which means that there is no significant difference between the estimated ET and ET calculated using Meteorological data. Hence, ET estimated using remote sensing method can be considered acceptable and more advantageous in that it can show spatial and temporal scales.

Spatio-temporal variations in ET for the different land cover results indicate that dense forest has the lowest mean ET of 5.39 mm/day (Table 4.5) hence it shows that the forest has the lowest water loss among the land covers. Perennial cropland has the highest mean ET of 5.83mm/day (Table 4.5) which indicates higher water loss and higher water requirements. Depending on the specific type of crop, irrigation may be required to sustain the agricultural water requirements. In general also, it is observed that cropland and grass land covers have the higher mean ET, an indication of higher water requirements.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The Objectives of the study were:

- To identify parameters for estimating ET
- To select suitable remote sensing data for estimating ET
- To estimate Spatial and temporal Evapotranspiration in Ndaka-ini Dam watershed between 2016 -2019.

These have been carried out and it can be concluded that:

- Estimation of ET using remote sensing method was demonstrated.
- Spatial and temporal distribution in estimated ET were mapped which is an advantage of this method over direct measurements method.
- Variations in land cover caused spatial changes in estimated ET within the study area.
- The estimated ET can help in water accounting and planning in the study area.
- Landsat OLI TIRS is a very useful dataset in estimating spatio-temporal ET at a watershed level and therefore it should be used for better representation of ET in

accounting for water loss. Despite the usefulness of Landsat 8 data, it poses some challenges because of its 16-days temporal resolution and cloud cover.

- Afforestation enhances water conservation

5.2 Recommendations

From the study, its recommended that:

- Remote sensing methods be applied for ET estimation in similar regions
- The results of the study be used by water resource managers plus other professionals in setting policies for watershed conservation for sustainable development
- To achieve sustainable water resources management mainly in agriculture, daily ET estimates at finer spatial resolutions should be done especially when looking at water consumption and requirements for different crops which informs irrigation.
- Further study be carried out on the applicability of remote sensing for ET estimation in monitoring regional and global water cycles.

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APPENDICES

APPENDIX 1: Landcover accuracy Assessment obtained from RCMRD

Class Name	Reference Totals	Classified Totals	Number Correct	Producers Accuracy	Users Accuracy
Dense Forest	280	272	216	77.14%	79.41%
Moderate Forest	188	214	148	78.72%	69.16%
Open Forest	125	145	94	75.2%	64.83%
Wooded Grassland	967	942	737	76.22%	78.24%
Open Grassland	535	566	395	73.83%	69.79%
Perennial Cropland	200	188	150	75%	79.79%
Annual Cropland	990	947	726	73.33%	76.66%
Vegetated Wetland	85	91	66	77.65%	72.53%
Open Water	45	43	36	80%	83.72%
Otherland	209	214	173	82.78%	80.84%
Totals	**3622**	**3622**	**3622**		

Overall Classification Accuracy = (2741/3622) 75.6347%, Kappa Coefficient = 0.7025

Classified Data	**Dense Forest**	**Moderate Forest**	**Open Forest**	**Wooded Grassland**	**Open Grassland**	**Perennial Cropland**	**Annual Cropland**	**Vegetated Wetland**	**Open Water**	**Other land**	**Total**
Dense Forest	216	4	0	14	7	5	25	1	0	0	272
Moderate Forest	11	148	3	23	5	3	20	0	1	0	214
Open Forest	5	3	94	20	11	1	10	1	0	0	145
Wooded Grassland	18	13	10	737	31	9	103	7	1	13	942
Open Grassland	2	6	6	70	395	4	67	4	0	12	566
Perennial Cropland	10	2	0	3	2	150	21	0	0	0	188
Annual Cropland	17	10	8	77	64	25	726	5	6	9	947
Vegetated Wetland	1	2	3	8	1	1	9	66	0	0	91
Open Water	0	0	0	2	0	1	1	1	36	2	43
Other land	0	0	1	12	19	1	7	0	1	173	214
Total	280	188	125	967	535	200	990	85	45	209	**3622**