Spatio-Temporal Distribution of Actual Evapotranspiration in Jhelum and Chenab Canal Irrigation System

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A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Remote Sensing and GIS

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Spatio-Temporal Distribution of Actual Evapotranspiration in Jhelum and Chenab Canal Irrigation System

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DEDICATION

Dedicated to my parents for their tremendous support and continuous prayers

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LIST OF SYMBOLS & ABBREVIATIONS

Symbols & Abbreviation	Explanation
ET	Evapotranspiration
ETa	Actual Evapotranspiration
ETp	Potential Evapotranspiration
ETO	Reference Evapotranspiration
ETc	Crop Potential Evapotranspiration
IBIS	Indus Basin Irrigation System
FAO	Food and Agriculture Organization
SEBS	Surface Energy Balance System
SEBAL	Surface Energy Balance Algorithm for Land
METRIC	Mapping Evapotranspiration at High Resolution with Internalized Calibration
SEBI	Surface energy balance Index
Rn	Net radiation
Go	Soil heat flux
H	Sensible Heat Flux
NDVI	Normalized Difference Vegetation Index
SAVI	Soil adjusted vegetation Index

LAI	Leaf Area Index
To	Surface Temperature
LAS	Large Aperture Scintillometer
α	Albedo
E	Surface Emissivity
Λ	Evaporative Fraction
λ	Latent heat of vaporization
$L\lambda$	Spectral Radiance
E	Latent Heat Flux
$RL\uparrow$	Outgoing Longwave Radiations
$RL\downarrow$	Incoming Longwave Radiations
ρair	Air Density
τsw	Atmosphere Transmissivity
PMD	Pakistan Meteorological Department
MODIS	Moderate Resolution Imaging Spectroradiometer
DEM	Digital Elevation Model
MRT	MODIS Reprojection Tool
NOAA	National Oceanic and Atmospheric Administration
AVHRR	Advanced Very High-Resolution Radiometer
USGS	United States Geological Survey

ABSTRACT

During the past few decades, fast increasing world population along with urbanization and industrialization has resulted in depletion of fresh water resources. In Pakistan agriculture plays a fundamental role in national economy which is mainly dependent on irrigated agriculture. Thus this sector is the main consumer of water. Evapotranspiration (ET) is key component of water cycle and its estimation in water scarce country like Pakistan plays an important role in water resources monitoring and management of irrigation discharge. The increase in water demand, due to population growth and economic development can affect the long-term water supply. The estimation of water consumption is also vital for distribution of water, the crop water requirement and enlargement of storage reservoirs. Several ground and remote sensing methods have been developed for estimation of evapotranspiration at various spatial and temporal scales. The ground based methods provide point measurements, the process is very hectic, time consuming and expensive and can only represent a small area compared to remotely sensed methods. The satellite remote sensing provides an opportunity for the estimation of Evapotranspiration over large areas. In present study ET is estimated in canal command areas of Jhelum and Chenab and the total area is 6.5 million acres. The Surface Energy Balance System (SEBS) model has been used for estimation of Evapotranspiration using moderate-resolution imaging Spectroradiometer (MODIS) data and Meteorological data obtained from Pakistan Meteorological Department. A large variation in Seasonal evapotranspiration has been observed. The ET values start increasing from March and the maximum values have been observed during the pre-monsoon season around 6.1 mm. This season starts from mid-April to June with hot short nights, long intense days with Peak temperature. The Evapotranspiration values have gradually decreased over the months and the lowest values have been observed in the winter season mainly in the month of January around 1.1 mm. The reason is the drop in the temperature along with the low soil moisture due to low precipitation in winter season. The surface energy balance algorithm (SEBS) is capable of estimating Evapotranspiration fairly well (R^2 0.87) as compared to the Reference ETo obtained from Pakistan Meteorological department at Regional Agro-Met station. The Results show that the remotely sensed datasets are useful for tracking changes in Evapotranspiration over large areas and with high temporal frequency. Among the various Meteorological variables, temperature followed by wind & sunshine significantly ($P<0.05$) impacted the evapotranspiration values,

whereas relative humidity has shown a negative trend. The variation in Evapotranspiration directly impacts the crop water requirement and these Evapotranspiration maps can help the water resource managers in monitoring water use and can help in irrigation management. A proper water management policy is mandatory in Pakistan to avoid severe water shortage in the near future. There is a need to drive precision agricultural technologies in Pakistan along with high efficiency Drip Irrigation techniques. These techniques will help the policy-makers in planning effective irrigation measures towards the sustainable development in Pakistan.

Chapter 1

INTRODUCTION

1.1. Background

During the past few decades, fast increasing world population along with urbanization and industrialization has resulted in depletion of fresh water resources. The human race is facing the issue of use of scarce resources like water in a reasonable and sustainable method. In an arid and semi-arid country like Pakistan water scarcity has become a serious issue. The scarcity is currently the main extreme danger to human beings and its surrounding environment. The scarcity has also affected the worldwide food supply. Moreover the contaminated water also has severe effect on human health. The amount of water accessible has an impact on a region's capability of food production. Over the years, the excessive use of this resource has led to its degradation and depletion universally. Many researchers in various parts of the world have already reported that there is an urgent need to improve water use efficiency in all sectors (Khan et al., 2008)

The increasing pressures to fulfill rising demands of water has increased competition between regions or countries for access to water, and tension is rising due to the fact that growing water demand is not synchronized with increased resources (Pulido-Calvo et al., 2007). The agriculture sector is considered the main consumer of fresh water with 70% of worldwide water extractions, while industry and urban uses are 20% and 10% respectively. It is becoming extremely difficult to preserve sufficient water for agriculture usage mainly due to climate change, increase in population and massive rise in water withdrawals. Therefore, agriculture through irrigation water supply is facing the problem in meeting the increase in food demand due to rising population. The loss of water to total evaporation is quite substantial, as daily water requirements usually surpass the amount of available rainfall and therefore the demands for water resources have to be supplemented by dams, water transfer schemes and irrigation systems, which utilize additional surface water and ground water resources (Gowda et al., 2007; Jarmain et al., 2009). Consequently the evaporation has become one of the key factors in irrigation water management, since accurate estimates of total evaporation assist in making well-informed decisions for various activities such as the design and management of irrigation schemes, regulating water laws and providing greater insight to hydrological studies (Bastiaansen, 2000; Bastiaansen et al., 2012).

In Pakistan agriculture plays a fundamental role in national economy which is mainly dependent on agricultural production. Pakistan's agriculture is largely based on the world's largest contagious Indus Basin Irrigation System (IBIS). Indus River basin is shared by Pakistan, India along with China and Afghanistan. Internationally shared bodies of water create political, social, and economic tensions and disputes concerning the distribution and use of resource management. Furthermore, when a resource base extends across a political border, misunderstandings or a lack of agreements about allocations are more likely (Conca et al., 2006). There is also a possibility of water-induced war between Pakistan and India which also poses a constant threat to regional stability.

Indus basin is largely dependent on water derived from the snow, glacier-melt along with rainfall-runoff. The water flowing in the Indus basin varies annually and it mainly relies on snow run-off melt in the Himalayan & Karakoram ranges. This makes the overall Pakistan's water resources and irrigation canal system very unique. The efficient use of water in agriculture sector is needed to meet future food demands. Improvements should be made in managing water resources in irrigated areas. Obtaining accurate estimates of total evaporation will enable water resources managers and practitioners to account for the loss of water from the land surface and to assist in the prevention of wastage which could have occurred previously (Bastiaansen, 2000).

Conventional techniques which are commonly used to estimate total evaporation, both locally and internationally, are confined to the field scale, providing point-based estimates (Bastiaansen, 2000; Su, 2002; Li *et al.*, 2011; Bastiaansen *et al.*, 2012). These techniques have been extremely useful in acquiring total evaporation data, however they only provide information at a local field level and generally cannot provide the estimation of evaporation over large geographic areas. This is largely due to the heterogeneity of land surfaces, which becomes more pronounced over larger geographical scales, as well as the changing nature of heat transfer processes at greater spatial scales (Bastiaansen, 2000; Su, 2002; Li *et al.*, 2011; Bastiaansen *et al.*, 2012).

The use of conventional techniques to estimate total evaporation over large geographic scales would prove to be impractical and somewhat costly (Elhaddad and Garcia, 2008; Badola, 2009; Bastiaansen *et al.*, 2012). The use of satellite earth observation is a very useful source with respect to biophysical parameters such as vegetation indices, albedo and land surface temperature. Satellite earth observation is able to provide information over large geographic scales, capture information which is not easily accessible through the use of conventional techniques and to provide time series data of variables fairly easily, due to the temporal updating of information (Sandholt *et al.*, 1999; Bastiaansen, 2000, Su, 2002; Jarmain *et al.*, 2009). There has been intensive research conducted on a global scale, to integrate satellite earth observation and hydrological modelling over the past few decades, with noteworthy advancements being made in the land/hydrologic satellite earth observation data integration (Bulcock and Jewitt, 2010; Xu *et al.*, 2014). However, there still remains a number of major challenges in this field that need to be overcome (Xu *et al*., 2014). This is largely due to the lack of appropriate technology required to handle and process satellite earth observation data and the lack of knowledge regarding the application of these techniques (Schultz and Engman, 2000: Bulcock and Jewitt, 2010; van Dijk and Renzullo, 2011). Satellite earth observation data possess a variety of benefits that can be used to assist water resources management.

1.2. Irrigation System of Pakistan

In Pakistan total cultivable land is about 22.27 million hectare and nearly area 81% is under irrigated agriculture in Indus Basin Irrigation System. The basin contains 46 canal commands with typical annual canal diversion of 127 billion m^3. The irrigation projects were constructed for the diversion of water supplies during wet Kharif season and fulfill the shortages between the provinces during dry Rabi season. The shortage is fulfilled by fresh water and groundwater across the basin both in terms of quantity and quality (Ahmad, 2005).

In Pakistan throughout the past seventy years since the independence there has been a substantial progress in the irrigated areas and cropping intensity in Pakistan because of the extension in the irrigation system. The rise in productivity during the same period was nearly twofold. Presently, canal water supplies cannot fulfill the water requirement of crops and this results in a severe shortage of production and net profit. The issue is more intensified mainly due to unequal supply of water due to conveyance losses.

Due to increase in water scarcity issues the irrigated agriculture will be essential for production with less water in the near future. A major limitation in estimating water consumption is the difficulty associated with its assessment and quantification. Measurement and estimation of evapotranspiration and its relationship with discharge in canals is a difficult task.

1.2.1 Crop Water Requirement and Irrigation Practices

The crop water requirement is defined as the amount of water required to meet the loss of water through evapotranspiration. It can also be defined as the amount of water required by the different crops for optimal growth i.e. a uniform crop, actively growing, completely shading the ground, free of diseases, and favorable soil conditions (including fertility and water). The crop therefore reaches its full production potential under the given environment (FAO-United nations).

The maximum crop water requirements are in hot and dry areas while the lowest requirement are found in cool and humid areas. The climate of Pakistan is semi-arid to arid and its agricultural efficiency depends upon the availability of water. The only way to expand agricultural production in Pakistan is through use of water resources efficiently. In Pakistan, major crops like wheat, rice, cotton and sugarcane are grown in canal command areas and water requirement is fulfilled from surface water mainly through a network of canals. There are massive water losses through canal based irrigation. Evaporation and infiltration losses cause huge shortages to crops because of overexploitation of water and hence water scarcity issues will have harmful impacts on the national economy.

Water shortage and scarcity cause degradation of land due to rain-fed agriculture (Suleimenov et al., 2011) and lower food production, particularly in the agricultural and semi-agricultural zones (Fraitureet al., 2010). Approximately 80 percent of the world's agriculture comprises rain-fed land, which produces 80 percent of the food globally (Falkenmark et al., 2001; Valipour, 2013).

Currently the agricultural sector is facing severe pressure to fulfill the food necessities of growing population. Higher yields is required in agriculture based country where population growth is increasing at a faster rate .The farmers in Pakistan usually practice open flooded systems to irrigate fields which results in poor water management and over-irrigation.

At sowing evaporation is dominant while after initial stages of crop growth transpiration becomes dominant. During the crop growth stage water requirement increases. At senescence maximum crop water requirement is reached. There are two main periods according to FAO. The fresh harvested crops whose water requirement remains same throughout the growth stage. The dry harvested crops reduce the water demand at the ending stages as they are allowed to dry hence no irrigation water is required. Evapotranspiration is one of the main components of the hydrologic cycle. Evapotranspiration varies according to crop types under different climatic conditions. Most of the crops in Pakistan demand irrigation due to high evapotranspiration. In Pakistan there is an issue of standing water on rice crops during the growing season to enhance the yields and this over irrigation leads to poor water use effectiveness. The Crop water requirements are mentioned below.

Table 1.1 Crop water requirements; Source (FAO - United nations)

Crop	Crop water need (mm/total growing period)
Alfalfa	800-1600
Beans	300 - 500
Citrus	900 - 1200
Cotton	700 - 1300
Groundnut	500 - 700
Maize	500 - 800
Rice	550-750
Sorghum/millet	450 - 650
Soybean	450 - 700
Sugarcane	1500-2500

1.3. Scope of the study

In Pakistan the agriculture by irrigation in the basins is the leading consumer of fresh water, thus fulfilling its water requirement is a big issue. Specifically, the estimation of water consumption by crops at a large spatial and temporal scale is essential. In a developing country like Pakistan having semi-arid to arid climate the circulation of annual rainfall is very irregular and much less than evaporative demand. Under growing water scarcity conditions, irrigated agriculture will be essential for production with less water in the future. The management of water resources in canal command areas and the assessment of irrigation discharge is a difficult task. Hence, the quantification of water balance components is fundamental for a clear understanding of various hydrological processes both spatially and temporally.

The models and tools related to climate and hydrology field can help as spatial decision support systems for managing the irrigation water supply in a sustainable way. The models require huge data as an input. The management of water resources is dependent on data being available at the required spatial and temporal scales. The use of satellite earth observation data alone is not seen as a solution to the current challenges of data acquisition, however it is a useful alternative in providing crucial data when conventional measures prove to be inadequate or unavailable (Jarmain *et al.*, 2009).

One of the main tasks in modelling land-atmosphere interactions is the estimation of evapotranspiration. The ET and its calculation is one of the main components of efficient irrigation planning and crop water requirement. The estimation of water consumption is also vital for distribution of water, fulfilling the crop water requirement and enlargement of storage reservoirs. The evapotranspiration estimation techniques are point based and they provide spatial coverage of the only local scale. On the other hand the satellite based remotely sensed data provides the estimation over large area. The various climatic and biophysical variables are required for estimation of ET at regional scales.

1.4. Research Objectives

The aim of the current research is the estimation of water loss through evapotranspiration that will help in implementation of food security measures for sustainable development. The obtained information will be useful for evaluation of water consumption that can help in irrigation planning, monitoring crop water use over time and can help in planning to reduce water loss by water conservation efforts.

Following are the objectives of the research.

A. The estimation of Actual evapotranspiration (ET) and its seasonal variations in Jhelum and Chenab Canal irrigation system**.**

B. To determine the impact of climatic and biophysical parameters on Evapotranspiration.

The research will be conducted using the satellite remote sensing data along with the meteorological stations data of Jhelum, Faisalabad and Toba Tek-Singh obtained from Pakistan meteorological department (PMD).

1.5. Evapotranspiration

Evapotranspiration (ET) is combination of two main procedures; evaporation of water from land and water surfaces, and transpiration from vegetation leaves. In evaporation, vaporization happens in which liquid water is changed to water vapor subsequently the removal of water vapors from the surface which can be lake, river, ocean or any other water body. Transpiration includes vaporization of water vapors from plant tissues into atmosphere. The two processes happen at the same time and are tough to distinguish. Evapotranspiration plays an important part in defining water budget. The irrigation water in Pakistan is lost due to evapotranspiration and excessive use of irrigation discharge due to lack to knowledge among the farmers. The improvements in water use should be based on accurate estimation of evapotranspiration. The water consumption generally varies locally, regionally and globally and ET varies according to climatic and biophysical variables.

The evapotranspiration is generally estimated as millimeter per unit time. The latent heat of vaporization is the heat or energy necessary for vaporizing liquid water. It is denoted by 'λ'. Energy for ET per unit area may also be represented in units of water depths. Latent energy depends upon the water temperature.

1.6. Types of Evapotranspiration

Evapotranspiration is basically divided into reference evapotranspiration (ETr), potential evapotranspiration (ETp) and actual evapotranspiration (ETa).

1.6.1. Reference Evapotranspiration (ETr)

Crop reference ET is the rate of evapotranspiration from a reference crop that is not short of water, which can be a hypothetical grass reference crop with specific characteristics (Allen et al., 1998). It is the evaporative demand of the atmosphere, independent of crop type, crop development and management practices. As the reference evapotranspiration describes the evaporative influence yet it does not include soil factors and lithology. Climatic variables are the main factors affecting ETr and can be computed from station based data, like in current research it was mainly acquired from Pakistan meteorological department.

1.6.2. Potential Evapotranspiration (ETp)

The potential evapotranspiration can be defined as maximum possible Evapotranspiration that can happen from a large area that has enough water available for ideal crop growth.

1.6.3. Actual Evapotranspiration (ETa)

The actual water used and transpired by crops, soil and vegetation in available energy and soil moisture conditions is represented by actual evapotranspiration (ETa) which is water transpired and evaporated from soil and vegetation in available energy and soil moisture conditions (Senay et al., 2007).

1.7. Factors affecting Evapotranspiration

The factors affecting evapotranspiration can be grouped into broadly three categories; climatic Parameters, crop parameters and environmental parameters. ETr is only affected by the climatic parameters due to non-dependence on crop or soil factors, whereas, ETa is affected by all these parameters and is thus challenging to estimate.

1.7.1. Climatic Parameters

Climatic parameters are the controller of the energy and responsible for the removal of moisture from atmosphere. The climatic parameters which affect evapotranspiration consists of temperature, precipitation, relative humidity, wind speed and sunshine or radiations. The amount of solar radiation are the main source of energy for evapotranspiration. The more the amount of energy reaching the surface, the more the evapotranspiration. The increased solar radiation increases the air temperature which increases evapotranspiration and hence, it is higher in sunny, warm days and less in cold and cloudy days. When the air humidity is high, air is saturated, has more moisture and less capacity of holding extra moisture, so ET is less. In dry atmosphere, the air has less moisture and can hold more moisture, so ET is high. The difference in vapor pressure affects the moisture removal capacity. If the difference is high, ET will be high and vice versa. Wind speed is responsible for exchanging the air above surface with air from surrounding areas which removes water vapor. When evapotranspiration occurs, the air above gets saturated and it is replaced with adjacent air masses which facilitates ET. When wind speed is high, the air is replaced quickly thus increases ET (Allen et al., 1998).

1.7.2. Crop related Factors

Various crop related factors affect ET in complicated ways which include but are not limited to crop type, variety, development stage, height, roughness, reflection, ground cover. Further, the diseases and stressed crops have different ET (Brown, 2014).

1.7.3. Environmental Factors

Evapotranspiration is also affected by environmental parameters which include soil salinity, soil fertility, fertilizer application, soil structure, diseases, and pesticides. Other factors that can affect ET is the water holding capacity of soil. The amount of water present in soil can increase Evapotranspiration but excess of soil water may result in waterlogging hampering crop growth which can reduce ET (Brown, 2014).

1.7.4. Importance of Evapotranspiration

ET is the major part of energy and water balance necessary for maintaining heat exchanges between land and atmosphere (Mutiga et al., 2010). In agricultural sector, it is important to identify water deficiency, crop stress, and crop water use (Hadjimitsis and Papadavid, 2013). It helps in studying the relation between climate and vegetation and its monitoring is necessary for maintaining agricultural production and tracking depletion of water resources (Maeda et al., 2011). It is also important for tracking evaporative depletion and studying its variability with respect to climate, soil moisture, crop factors etc. (Yang et al., 2012). ET in combination with land use information help in allocation of water to different sectors like agriculture, natural environment and industries.

Chapter 2

LITERATURE REVIEW

2.1. The Evapotranspiration estimation methods

There are a huge number of evaporation models available for accurate estimation at local and regional scale. The commonly used models include the Surface Energy Balance Index (SEBI), the Surface Energy Balance Algorithm for Land (SEBAL), the Surface Energy Balance System (SEBS) and Mapping Evapotranspiration at High Resolution with Internalized Calibration (METRIC). These models measure ET based on various properties such as climatic parameters, vapor transfer measurement, water balance, atmospheric stability etc. The broad categories of ET estimation methods are direct field measurement methods, indirect estimation methods and remotely sensed methods.

2.1.1. Direct Field Based Methods.

The field estimation techniques are based upon either measurement of evapotranspiration as a loss of water by measuring other components or the measurement of water vapor flow as mass or energy balance by different sensors (Shuttleworth, 2008). These methods measure ET mostly at field scale except water balance technique which is applicable at basin scale.

2.1.1.1. Water Balance

In water balance model evapotranspiration is measured as a residual term when all other components of water balance are estimated and the difference of these components results in ET. The amount of water incoming and outgoing from soil is measured where irrigation and rainfall add water to soil and soil water evaporation and crop transpiration remove water. The ET is measured from assessing change in soil water content but this method can only give ET estimates over week or longer (Allen et al., 1998) as it gives area-weighted measurements which can be difficult and expensive to measure for components like soil moisture and groundwater (Shuttleworth, 2000)

2.1.1.2. Lysimeters

Lysimeters are controlled setup mainly tanks containing soil. The crops are grown under natural conditions to assess evaporation and transpiration (Yang and Zhang, 2009). The basic principle of working of Lysimeters is water balance but the difference is that the same conditions are matched in a container where the measurements are done. In a separate tank the soil is placed and plants are grown where the water movement is measured and water balance equation is solved with ease. The water loss in weighing Lysimeters is measured by change in mass, whereas, in non-weighing, water loss is estimated from the drainage water in tank after use. One major requirement for accurate estimation is to exactly match the conditions in tank to field conditions, otherwise it will result in erroneous results. The Lysimeters are dependent upon sample and are often not representative of field and represent point measurements (Rana and Katerji, 2000). They are also expensive and difficult to operate (Allen et al., 1998)

2.1.1.3. Bowen Ratio technique

Bowen (1926) proposed a method for estimation of evapotranspiration which is now one of the most renowned energy balance techniques used for ET estimations. Bowen Ratio measures the ET by energy balance.

Starting with the basic energy balance equation, dividing both sides by λE and solving the equation gives:

$$\lambda E = Rn - G / 1 + \beta \quad (2.1)$$

Where β is the Bowen Ratio which is the ratio of sensible heat flux to latent heat flux. Rn is net radiations and G is soil heat flux.

2.1.1.4. The Aerodynamic Method

In aerodynamic method the latent heat is estimated through friction velocity and humidity.

$$\lambda E = P\lambda \, u^* \, q^* \quad (2.2)$$

Where P is air density and u^* and q^* are calculated from wind and humidity measurements. Because the precise estimations of various heights above the crop is hard, Rana and Katerji (2000) proposed much simple types of the aerodynamic method based on the calculation of wind speed & temperature at two heights only.

2.1.1.5. Large Aperture Scintillometer (LAS)

In LAS a light beam is used for measurement of the vertical wind fluctuations which are caused by eddies due to temperature and air moisture variations from which sensible and latent heat can be calculated. Because of the wind, sensible heat is estimated over an area rather than point measurement from light beam which can extend up to numerous kilometers. This method has bigger scale than other direct field measurement methods and can be applied from field to landscape scale (Kite and Droogers, 2000; Shuttleworth, 2008).

2.1.2. Indirect Estimation Methods

As the field methods of ET measurement are expensive and difficult to operate therefore ET is computed mostly from the weather data obtained from weather stations including temperature, humidity, wind speed, and vapor pressure etc. These weather data are used to compute ETr from which ET of crop is calculated using crop coefficients (Kc). The ETr estimation methods fall into three categories i.e. combination, radiation and temperature methods.

2.1.2.1. Combination Methods

The combination methods utilize both radiation and temperature measurements in the calculation of ETr. These methods require the extensive amount of accurate weather data. Combination methods include Penman Method and FAO-56 Penman-Monteith method. Penman method was given by Penman (1948) and it uses radiation, pressure, air temperature and wind speed data. It uses aerodynamic approach i.e. the difference of temperature between two heights along with net radiation not considering any ground heat exchange or storage.

The FAO-56 Penman-Monteith is widely used to estimate reference ETr from alfalfa or grass crop with particular characteristics. Reference ET does not depend upon type of crop, crop development stage and management practices but it represents atmospheric demand of evaporation at a particular time of the year and at a specific location. ETr from the same reference surface are comparable for different locations. ETr is also a climatic parameter as it depends only on climatic parameters, and it is calculated from weather data. The FAO-56 technique is considered the only technique for calculation of reference evapotranspiration from meteorological data. From the aerodynamic and canopy resistances equations and original Penman-Monteith equation, the equation can be described as

$$ETr = (0.408\ \Delta\ (Rn - Go) + \gamma\ 900/\ (T + 273)\ u2\ (es - ea))/\Delta + \gamma\ (1+0.34u2) \quad (2.3)$$

Where ETr is the reference ET [mm day^{-1}], Δ the slope of temperature saturation vapor pressure curve [kPa$°C^{-1}$], Rn the net radiation flux [MJ $meter^{-2}$ day^{-1}],Go the soil heat flux [MJ meter-^{2} day^{-1}], γ the psychrometric constant [kPa $°C^{-1}$], T the air temperature [^{o}C], U2 the wind speed at 2 meter height [meter sec^{-1}], es the saturation vapor pressure [kPa], ea the actual vapor pressure [kPa], (es- ea) the saturation vapor pressure deficit [kPa].

This technique is a standard for calculating ETr and uses aerodynamic components and surface resistance for calculating ETr which requires large amount of data. The conditions are typical of uniform, healthy and well-watered green grass. Using a reference crop for calculations allows the method to serve as standard for comparing ET at different times, places and crops.

2.1.2.2. Radiation Methods

Radiation methods remove the need of humidity and temperature data and most common is Priestley-Taylor method (Priestley and Taylor, 1972). This technique does not use wind speed and humidity data and calculates ETr without aerodynamic component. It measures ET from well-watered evaporating crops and it is not suitable for measurement in arid irrigated crops (Dodds et al., 2005).

2.1.2.3. Temperature Methods

Temperature methods use temperature data in ET estimation. These methods are used when other data are not available. Hargreaves and Blaney-Criddle are two such common methods. Hargreaves method uses a relationship between temperature and humidity, whereas, Blaney-Criddle uses mean temperature and sunshine hours for ET calculation.

2.1.2.3.1. The Thornthwaite Method

Thornthwaite (1948), produced a link among temperature and the evaporation rate developed from catchment water balance studies. The method required temperature as the meteorological parameter. The method, take the general form as

$$ET = cTa \tag{2.4}$$

Or

$$ET = c_1 d_l T\ (c2 - c3h) \tag{2.5}$$

Where ET is evapotranspiration, T is air temperature, h is a humidity, d_l is day length and the rest are constants. The equations are standardized for the climatic region and time period in which they were established and these can be prone to errors when they are extrapolated to some other areas. Thornthwaite's method has been widely used in arid and semi-arid irrigation areas (Jensen et al., 1990).

2.1.2.3.2 The Blaney-Criddle method

Blaney and Criddle (1942) developed the method for estimation of water necessities in irrigated lands having limited meteorological data. The aim was to apply the experimental results over the entire western United States for estimation of evapotranspiration and irrigation water requirements. Blaney and Morin (1950) later produced empirical equation to estimate annual evaporation from free-water surfaces.

This relationship is described as;

$$U = ktp\ (114 - h) = kc \qquad (2.6)$$

Where;

u = monthly consumptive use [inches]

k = “vegetation” coefficient derived from measured use

t = mean monthly air temperature [°F]

p = monthly percentage of annual daytime hours

h = mean monthly relative humidity [%]

2.1.2.3.3. The Hargreaves method

Hargreaves and Samani (1985) established an empirical equation through min and max air temperature. The basis is the Hargreaves (1975) equation for the calculation of reference crop evapotranspiration from radiation and temperature.

$$ET = 0.0135R\ (T + 17.8) \qquad (2.7)$$

Where ETo and the solar radiation Rs incident on the surface are both expressed in depth of evaporated water and T is mean temperature.

2.1.2.4. Crop ET from Crop Coefficient

The crop ET is found out using crop coefficients which are developed related to crop growth and parameters. The crop ETr is related to crop coefficient Kc in ETr×Kc form to find out actual crop ET. Kc represents the crop canopy and resistance and represents specific crop characteristics. Kc is affected by crop patterns, climate, soil evaporation and crop growth stages

(Allen et al., 1998). This is the main method for irrigation management and FAO maintains databases of Kc (Glenn et al., 2007).

2.1.2.5. Crop ET from Pan Evaporation

The evaporation from pan represents the effects of various factors on evaporation of water including temperature, humidity and wind. Generally, when there is no precipitation, evaporation from pan is measured as decrease in depth of water in mm. But the water lost by evaporation is significantly different from the water lost from crops and is higher than crop ET. The radiation from pan can be different, the heat storage in pan can also cause evaporation at night and also the temperature, humidity conditions above pan can all result in different ET. So, pan evaporation is related to ETr using pan coefficient Kp by the function ETr=KP×Pan Evaporation (Allen et al., 1998).

2.1.3. Energy balance methods using Remote Sensing

The satellite based techniques have been developed recently and put into use the various kinds of satellite data including National Oceanic and Atmospheric Administration/Advanced Very High-Resolution Radiometer (NOAA/AVHRR), MODIS and Landsat. The satellite records the measurements over large areas and help in effective study of spatial variations. They have advantage over other methods due to their less cost and ease of applications. Remote Sensing methods for ET estimations are diverse. Two broad categories based on remote sensing are using vegetation indices and surface energy balance model.

2.1.3.1. Vegetation Indices Methods

These methods make use of various vegetation indices derived from the satellite data for calculation of ET as these indices are representative of vegetation density and amount. NDVI is most common vegetation index with SAVI being another one. LAI is another index that is commonly used for ET estimation and represents ratio of leaf area to ground coverage. One drawback of this method is requirement of ground calibration.

Nagler et al. (2005) estimated ET using MODIS data along western US Rivers. Enhanced Vegetation Index was calculated from MODIS which was strongly correlated to ET estimates from towers and with inclusion of air temperature the correlation improved further. 16-day composite of vegetation index and temperature were used to predict ET (R^2= 0.74). The study found out lower estimates of ET than those from water budget estimates of area. In another study, Nagler et al. (2013) estimated ET of riparian and agricultural vegetation using ETr and MODIS enhanced vegetation index and the algorithm was calibrated with ET from eddy covariance towers with R^2 of 0.73. The results were compared with water balance and tower data and errors were within 10%. The study concluded that the method could be used for estimating ET using vegetation and ETr data over dry land irrigated and riparian areas but cannot be extended to other areas.

2.1.3.2. Surface Energy Balance Methods

These methods make use of the satellite data for estimating various components of energy balance like net radiation, sensible heat flux and soil heat flux for the calculation of ET as a residual of these components. They involve conversion of satellite data into variables like albedo, reflectances, vegetation indices, surface temperatures that are used to calculate energy balance.

Senay et al. (2007) used Simplified Surface Energy Balance (SSEB) model with MODIS NDVI and thermal data to measure seasonal ET in irrigated agriculture river basin Kabul and Helmand in Afghanistan over six years (2000-2005). They concluded that cropping patterns of the region affected temporal ET representing water use pattern. Bawazir et al. (2009) calculated ET using surface energy balance approach in Rio Grande Basin, USA and compared the estimates with eddy covariance flux towers. They found out the Mean Square Error (MSE) for salt cedar and cottonwood as 0.16 and 0.37 $mmday^{-1}$ and the variations in ET were due to plant type, density, soil type, moisture and water table depth.

Jin (2009) computed ET using Surface Energy Balance System (SEBS) with cloud free AVHRR images for period from 1990-2004 in Zhangye basin, China. He found out that the annual ET increased gradually over years at rate of $0.21 \times 108\ m^3$ per year due to increase in vegetation cover. Li et al., (2012) used data from AVHRR with meteorological and in situ data to estimate ET over Heihe River Basin with evaporative fraction model and found out higher ET values in inland river basin than in heterogeneous areas and desert where vegetation is dense and continuous and vary with crop development stage. They also found out that high soil moisture can result in high ET despite of low vegetation.

Apart from vegetation index and energy balance models, there are some other techniques of estimating ET using remote sensing. Some of these attempt to make use of standard ETr algorithms by incorporating the parameters computed from satellite data. Farg et al. (2012) used SPOT-4 satellite data to compute Kc for wheat crop and integrated it with ETr computed from FAO Penman-Monteith method. NDVI and SAVI were calculated from SPOT-4 images from which Kc prediction equations were developed by multiple regression for developing, mid-season and late-season. Some of them are based on hydrological modelling approaches employing various hydrological models to compute ET. (Mu et al., 2011).

2.1.3.2.1. TSEBS Model

It considers the energy balance of soil and vegetation components individually and then estimates evapotranspiration through combination of these components. However extra meteorological data is needed for the application of this method. It requires some assumptions to manage the variations between radiometric surface and aerodynamic temperatures to partition surface energy balance into soil and vegetation components using either a single view angle or from multiple view angles (Ullah, 2011). Gowda et al., (2008) reported that the performance of TSEBS is not influenced by regional advections.

2.1.3.2.2. Surface Energy balance system (SEBS) Model

SEBS was established to estimate atmospheric turbulent fluxes with the help of satellite Earth observation systems. SEBS (Su, 2002) consists of a set of tools for the determination of the land surface variables like albedo, emissivity, temperature, vegetation indices from spectral reflectance, for the estimation of the roughness length for heat transfer (Su et al., 2001) and for the estimation of the evaporative fraction on the basis of energy balance in limiting cases. SEBS needs three sets of input datasets like land surface, meteorological, downward shortwave and longwave radiation that can either be direct measurements, model output or parameterization.

2.1.3.3.2. Surface Energy Balance Algorithm for Land (SEBAL)

Among various models, more common and with fewer requirements of ground data is SEBAL which has become one of the most successful models. It was first described by Bastiaanssen in 1998 (Bastiaanssen et al., 1998) for Egypt, Spain and Niger and then applied for many basins. Various studies have used SEBAL for ET estimations. Ahmad et al. (2005) used SEBAL to assess ET in Olifants Basin, South Africa using Landsat 7 ETM+ data of rainy season and found that the ET was highest for irrigated areas and higher than ETr value from Penman-Monteith equation. 25% of ET was from agricultural land use and irrigation contributed about 4% of basin ET.

Ahmad et al. (2006) computed ET in Krishna Basin, India using Landsat 7 image with SEBAL and found out that irrigated agriculture ET depends upon the crop growth stage. They found out that wastewater irrigated area had highest ET and grass ET was lowest. Teixeira et al. (2009) used Landsat TM from 2001 to 2007 and agro-meteorological data with SEBAL to compute ET, biomass in Brazil. They found out that ET for irrigated crops was higher than vegetation. Mutiga et al. (2010) used SEBAL for ET estimation in drainage basin of Kenya for 2000, 2003 and 2006. They concluded that ET increased gradually at a rate of 15% and that NDVI and altitude have high impact on ET with R^2 of 0.6048 and 0.32 respectively. They compared results with water balance and obtained correlation of 70%. They also found that although SEBAL overestimated ET as compared to FAO-56 method, the estimates correlated well with one another with R^2 0.7499. Sun et al. (2011) estimated evapotranspiration in China using SEBAL with Landsat ETM data and Meteorological data. The results of ET estimates from SEBAL were validated with those obtained from pan observation data and an overestimation of 10.8% deviation from daily estimates was found.

Yang et al. (2012) estimated ET using SEBAL with MODIS data in an irrigation district of North China from the period of 2000 to 2010. They found that ET over agricultural areas is controlled by Reference ET which is affected by crops whereas in other areas, precipitation affects ET. They tested the SEBAL performance against in situ measurements on field level. Li et al. (2013) used SEBAL with Landsat 5 data to compute ET of Yellow River source region in 2006 and found that ET was highest in grassland and lowest in bare soil. They also computed the relation of biophysical variables with ET and found out that temperature has highest correlation of 0.802 with ET.

Du et al. (2013) used SEBAL with MODIS and meteorological data to compute ET over Sanjiang Plain, China for 2006 growing season. They found out that SEBAL misestimated at 10.52% compared to eddy covariance and was within 8.86% deviation from ground observation. They found out that ET increased up to June or July and then decreases with vegetation. SEBAL has been validated and found that the seasonal ET were within 5% error of other ET methods and daily ET were less than 15%.

Thoreson et al. (2009) compared ET estimations from SEBAL, water balance and crop coefficients approach and found that SEBAL estimations were close to water balance with less than 1% difference as compared to difference of 14% for crop coefficient approach. The monthly percent difference varied from -2.7% to just over 30% due to error in soil water storage calculation, whereas, annual estimate has less error. A number of tools are presented within the Model, which integrate meteorological data and satellite earth observation data to estimate daily total evaporation (Su, 2002). Su (2002) states that the primary sets of data required by SEBS to estimate the daily total evaporation for any region. The data are obtained from two sources like satellite earth observation systems measuring spectral reflectances and radiances of the land surface and meteorological stations.

In addition to the various SEBS pre-processing functions available in ILWIS, SEBS possesses the added advantage of determining variables such as albedo, fractional vegetation cover and NDVI, amongst others (Su, 2002). The open-source nature of SEBS as well as the previously described advantages make it a promising tool for decision support system in water resources research, planning and management.

2.4. Evapotranspiration Estimation in Pakistan

Evapotranspiration has conventionally been estimated with the help of water balance and meteorological data from weather stations. Rasul and Mahmood (2009) calculated evapotranspiration in numerous climatic environments of Pakistan using radiation method, Modified Penman method, Bradley and Criddle Formula and FAO Penman-Monteith Equation. They discovered that FAO 56 equation performed better in all climatic settings.

Ullah et al. (2001) estimated the evapotranspiration in Indus Basin. It was found out that the annual ETr was lower (1200-1300 mm) in upper basin due to mild climate and higher (1700-2100 mm) in lower part covering Southern Punjab and Sindh. The maximum values of evapotranspiration were found in the summer season mainly in the month of June while minimum in winters in the month of December.

Sarwar and Bill (2007) estimated evapotranspiration with the help of ASTER datasets in Indus Basin by surface energy balance approach and meteorological data. The evapotranspiration calculated was in a range from 0-4.5 $mmday^{-1}$ and was in close agreement with estimations from hydrological model CROPWAT though the water evaporation was less than that from pan evaporation. The ET of sugarcane was less due to initial growth stage and was slightly higher for maize and cotton due maturity of crops.

Bastiaanssen et al. (2002) calculated evapotranspiration using SEBAL in Pakistan. SEBAL model was used with NOAA AVHRR, sunshine duration and wind speed data for calculation of evapotranspiration in Indus basin and results were validated with the help of various field-based models. They concluded that Rabi ET ranged from 300-400 mm and was higher for Punjab than Sindh. ET values in kharif period was higher (600 mm) than ET values in Rabi period due to higher radiations and high precipitation in the area.

Sultan and Ahmad (2008) used SEBAL with Landsat 7 ETM+ and meteorological data for evaluation of evapotranspiration values in Chenab canal irrigation system. The study found out that high ET is in upper areas including Sargodha and Mandi Baha-ud-din and low values in lower areas like Jhang. The evapotranspiration results were compared with the ET computed using Kc and ETr and found that ET accuracy assessment was up to 95% in Faisalabad, 90% in Jhang and 83% in Sargodha.

Liaqat et al. (2015) studied the application of SEBS model to evaluate spatial variations in water consumption and for the mapping of water consumption in Indus basin irrigation system. The evapotranspiration calculated by surface energy balance algorithm were significantly controlled by temperature values. The climatic and biophysical parameters used in the study gave important information of evapotranspiration. The surface energy balance models were recommended for calculation of water consumption in semiarid to arid countries like Pakistan.

Chapter 3

Materials and Methods

3.1. Study Area

Several canals and water courses irrigate a large area of Punjab province Pakistan. The research has been conducted on the Jhelum canal and Chenab Canal Irrigation System. Upper Jhelum Canal off takes from Mangla head works on Jhelum River. It was designed in 1904 and commissioned in 1915 primarily as a feeder channel to supplement the supplies of Khanki head works at Chenab River for Lower Chenab Canal system. It has total length of 142 km and cultivable command area is around 603749 acres. Upper Jhelum canal also fulfils the water requirements of Khanki headworks on River Chenab during low flows in river Chenab. Lower Jhelum Canal System originates from the Jhelum River at Rasul Barrage. (Figure 3.1)

The Chenab canal system was constructed between the years 1892-1898 and it is one of the earliest irrigation systems of the Punjab province in Pakistan. The Chenab canal irrigation system lies between the Chenab River and Ravi River. The study area lies between latitude 30°36' to 32°09'N and longitude 72°14' to 74°E. Khanki Head Works in Gujranwala District was constructed on the river Chenab for diversion of water. The water from Chenab canal system irrigates around 3.031 million acres cultivable command area of seven districts of Punjab. The irrigation system of LCC is one of the oldest irrigation schemes of the Indus Basin Irrigation system. The remote sensing techniques can be used for the better assessment and management of irrigation water supply. Lower Chenab canal irrigation system is separated into two parts, LCC-East and LCC-West. LCC-East consists of four branches, Mian Ali, Upper Gugera, Lower Gugera and Burala Branch while the LCC west has three branches namely Sagar, Rakh and Jhang Branch. The total canal command area of study region is around 6.5 million acres

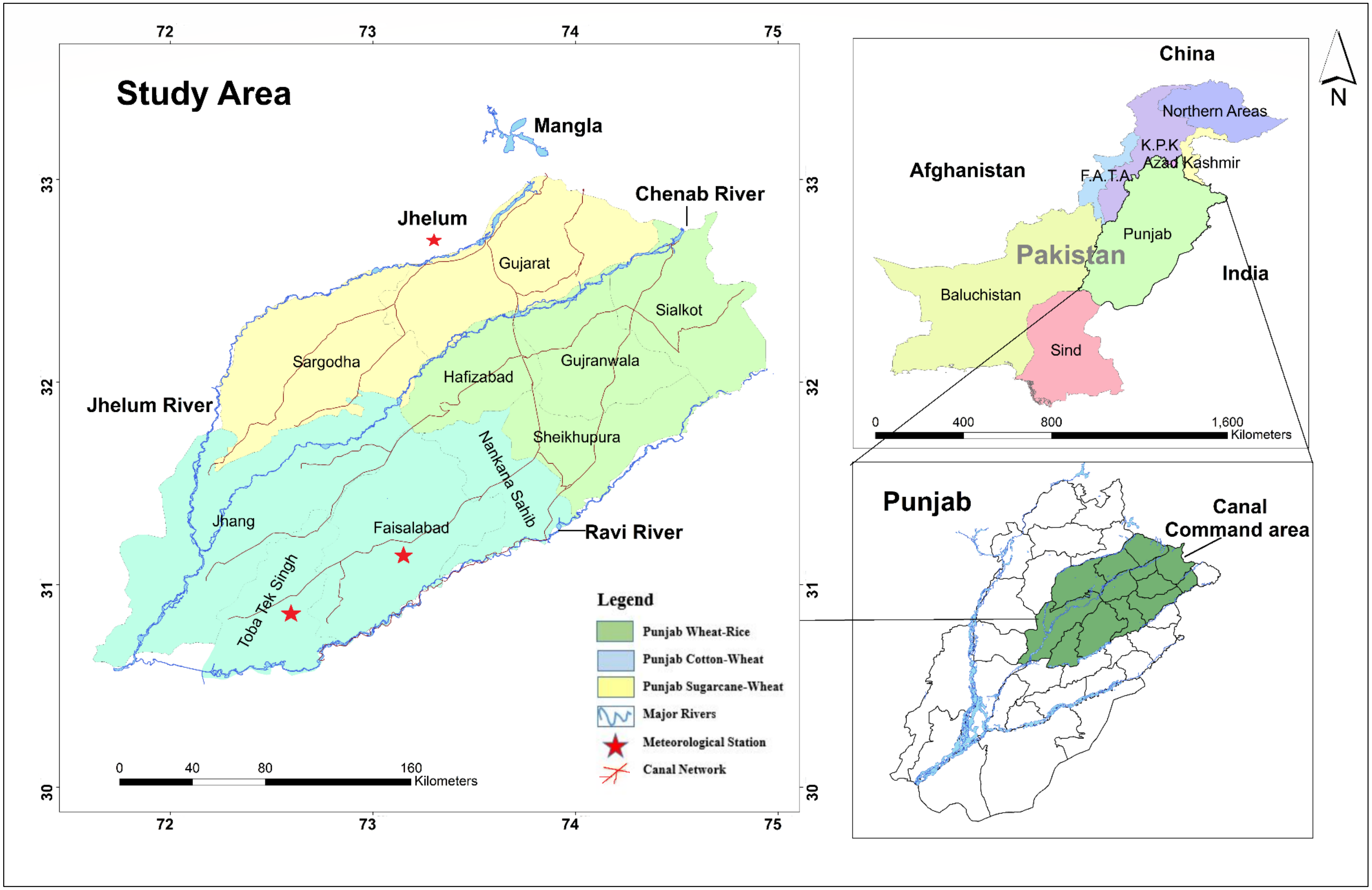

Figure 3.1. Map showing the study area

3.1.1. Climate

The climate of study area is semi-arid to arid with large seasonal variation of temperature and precipitation. The summers are hot with temperatures variations in a range of 21 to 41^0C whereas days in winter season are shorter and less intense solar radiations with temperature range is 1^0C to 25^0C. (Figure 3.2). The precipitation varies annually in the region with an annual precipitation of 250-300 mm. The highest precipitation is recorded during the monsoon period from July to September as shown in Figure 3.3. Data have been obtained from two weather stations installed by Pakistan Meteorological Department (PMD) in Jhelum, Faisalabad and Toba Tek-Singh. The comparison of the precipitation data have revealed an increase in precipitation in the recent years. The temperature and precipitation varies seasonally in the study area. Figure 3.2 and 3.3 shows monthly weather data of precipitation, minimum, maximum temperature for years 2001-2002 and 2015-2016 recorded at the PMD weather stations.

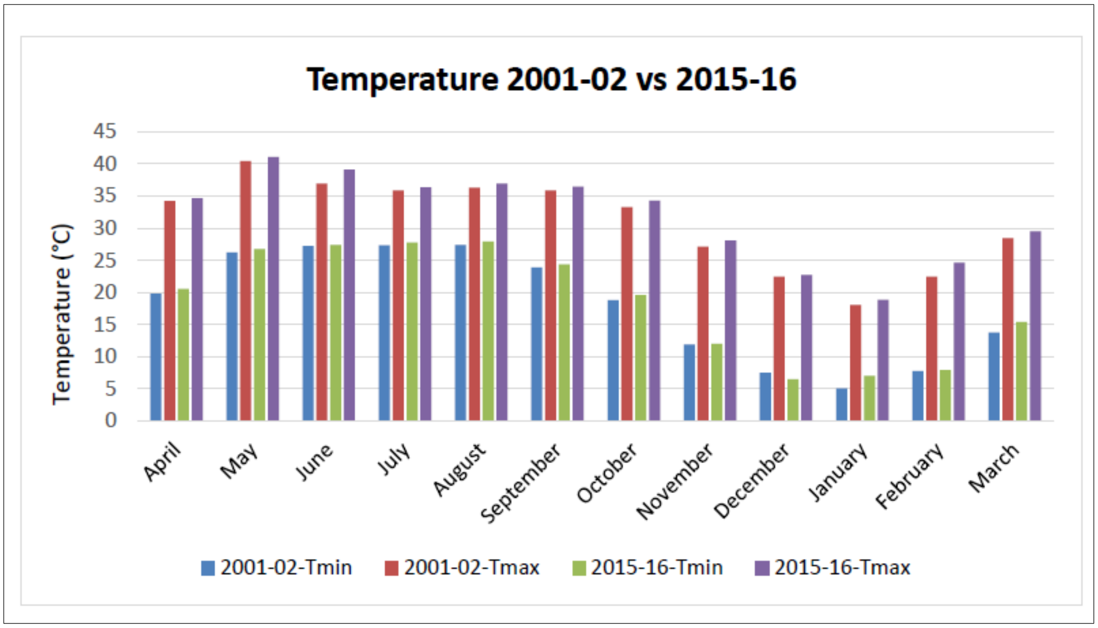

Figure 3.2. Temperature data for the years 2001-02 and 2015-16

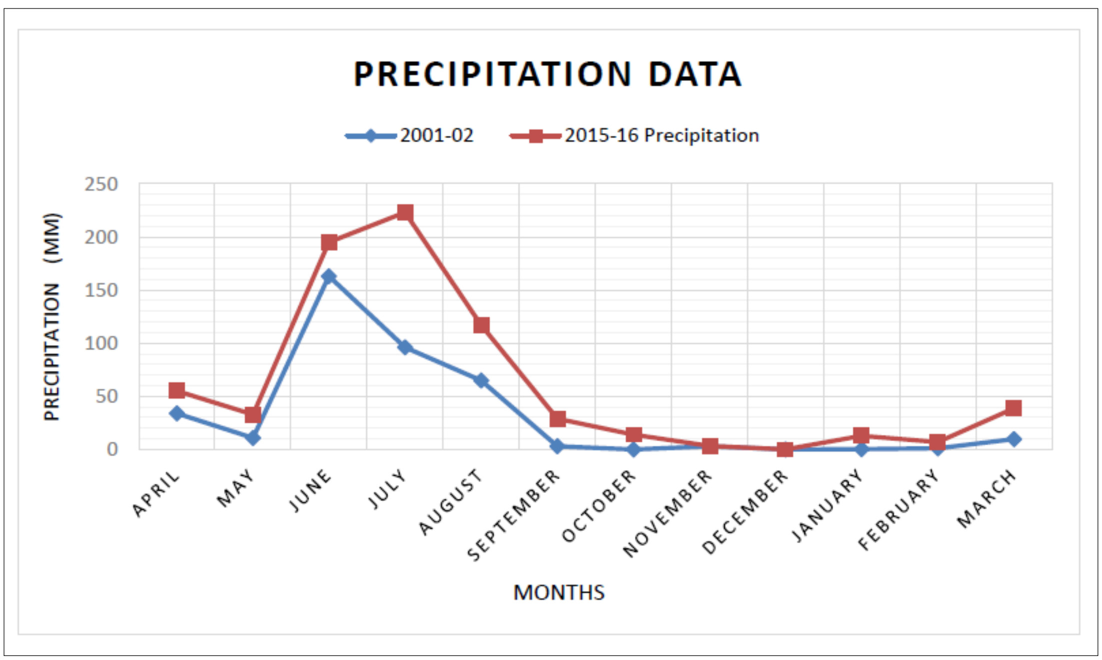

Figure 3.3. Precipitation data for years 2001-02 and 2015-16

3.1.2. Cropping pattern and Characteristics

The main crops cultivated in the study area are wheat, Cotton, rice and sugarcane. The two main cropping seasons are Rabi which starts from October and continues till March and Kharif season is from April to September. Wheat is the major crop during the winter season (Rabi) and rice, cotton in the summer season (Kharif). Sugarcane is an annual crop and also cultivated in some parts of the study area. Water requirement of these crops are fulfilled from surface water mainly through a network of canals. The crop calendar is given below.

Table 3.1 Crop calendar of study area.

CROPS	MONTHS													
	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	April
Wheat									Sowing	Growth				Harvest
Sugarcane	Sowing	Initial Growth			Maturity							Harvest		
Cotton			Sowing		Growing			Harvest						
Rice				Sowing	Growth			Harvest						

The rice-wheat is the main cropping system in the study area. The rice-wheat growing areas in Punjab are situated in districts of Gujranwala, Hafizabad, Sheikhupura and Sialkot. The sugarcane is mainly grown in Sargodha division. There is also a wheat-cotton rotation in areas of Faisalabad, Nankana sahib, Jhang and Tobatek Singh. Overall the study area is a mixed cropping zone as shown in Figure 3.4. The area covered by the crops are shown in Table 3.2 and the data is obtained from Punjab Bureau of statistics.

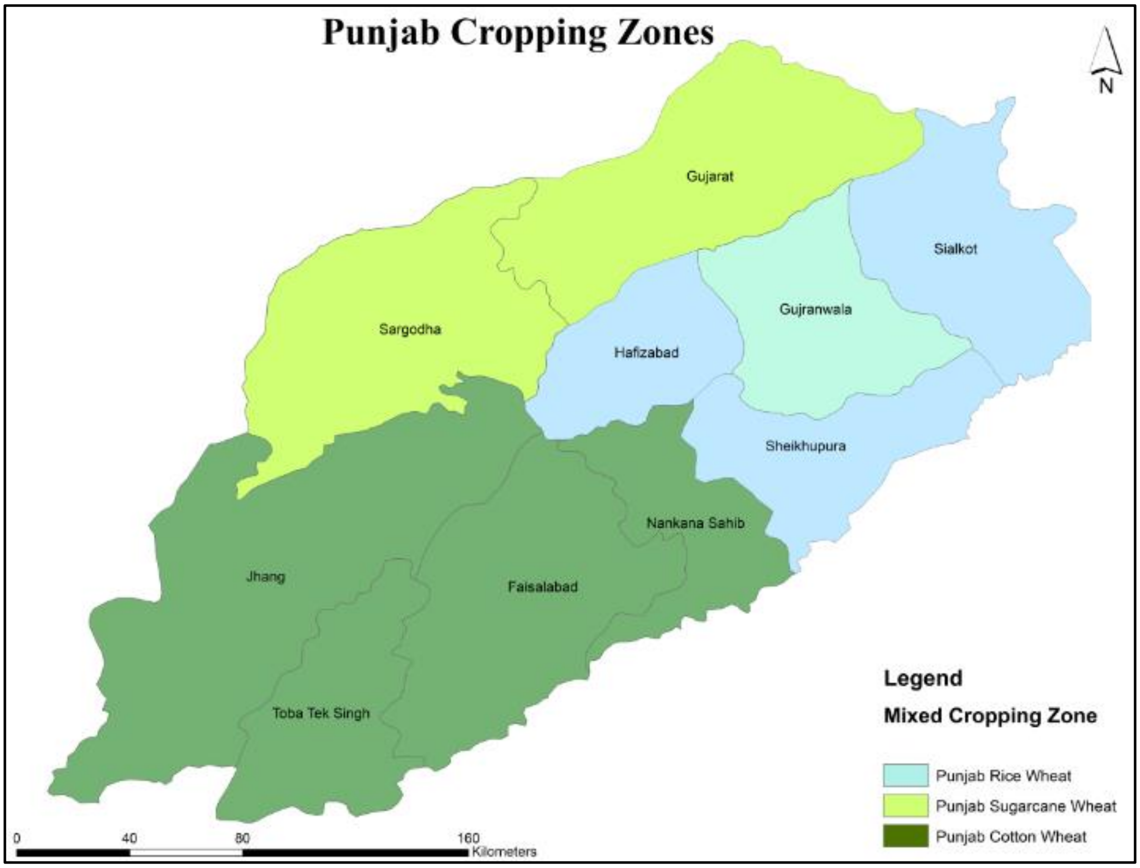

Figure 3.4 The Cropping zones present in study area.

Table 3.2. Area covered by crops in study region; Source Punjab Bureau of statistics

Crops	**Reported Area (Ha)**
Wheat	2,001,000
Rice	1,065,800
Cotton	346,000
Sugarcane	272,950

3.2. Methodology.

The Methodology adopted for the research work is given below and detailed flow diagram is shown in Figure 3.5.

3.2.1. Data Acquisition and processing.

The SEBS model requires various input parameters like albedo, Surface emissivity, land surface temperature, vegetation indices values and the meteorological factors like temperature, precipitation humidity, and wind speed. The incoming shortwave and the outgoing long wave solar radiation can be attained from albedo, Solar zenith and azimuth information.

The Moderate Resolution Imaging Spectroradiometer (MODIS) with high temporal frequency has been used before for the improved monitoring of land, atmosphere and ocean research. MODIS sensor is supported by both Aqua and Terra satellites. TERRA/MODIS observe the entire earth every one to two days, with a swath of 2400 kilometer. MODIS acquires data in 36 spectral bands. The bands have three different types of spatial resolution of 250-meter, 500 meter and 1000 meter. MODIS products are in a tile-based system, and each tile covers an area of 10^{o} by 10^{o} at equator (approximately1200 km by 1200 km). Due to the geographic locality of the study area, MODIS tile labeled H24V05 was used for the period of April 2001 to March 2002 and April 2015 to march 2016.

Table 3.3. Details of the required datasets.

Dataset	Description	Sources
Meteorological Data	Precipitation (mm) Temperature (^{0}C) Relative Humidity (%) Wind speed (km/hr) Sunshine (hrs.)	Pakistan Meteorological Department (PMD)
Remote Sensing Data	MODIS Datasets Digital Elevation Model (DEM)	NASA's USGS ASTER Global DEM
Ancillary Data	Major Rivers and Pakistan admin boundary	Survey of Pakistan

3.2.2. Digital Elevation Model (DEM)

ASTER Global digital elevation model (G-DEM) with 30 meter spatial resolution was used for carrying out the research work. The input parameters for SEBS model had a spatial resolution of 1000 meter, therefore ASTER DEM was also projected into 1000 meter to match the spatial resolution.

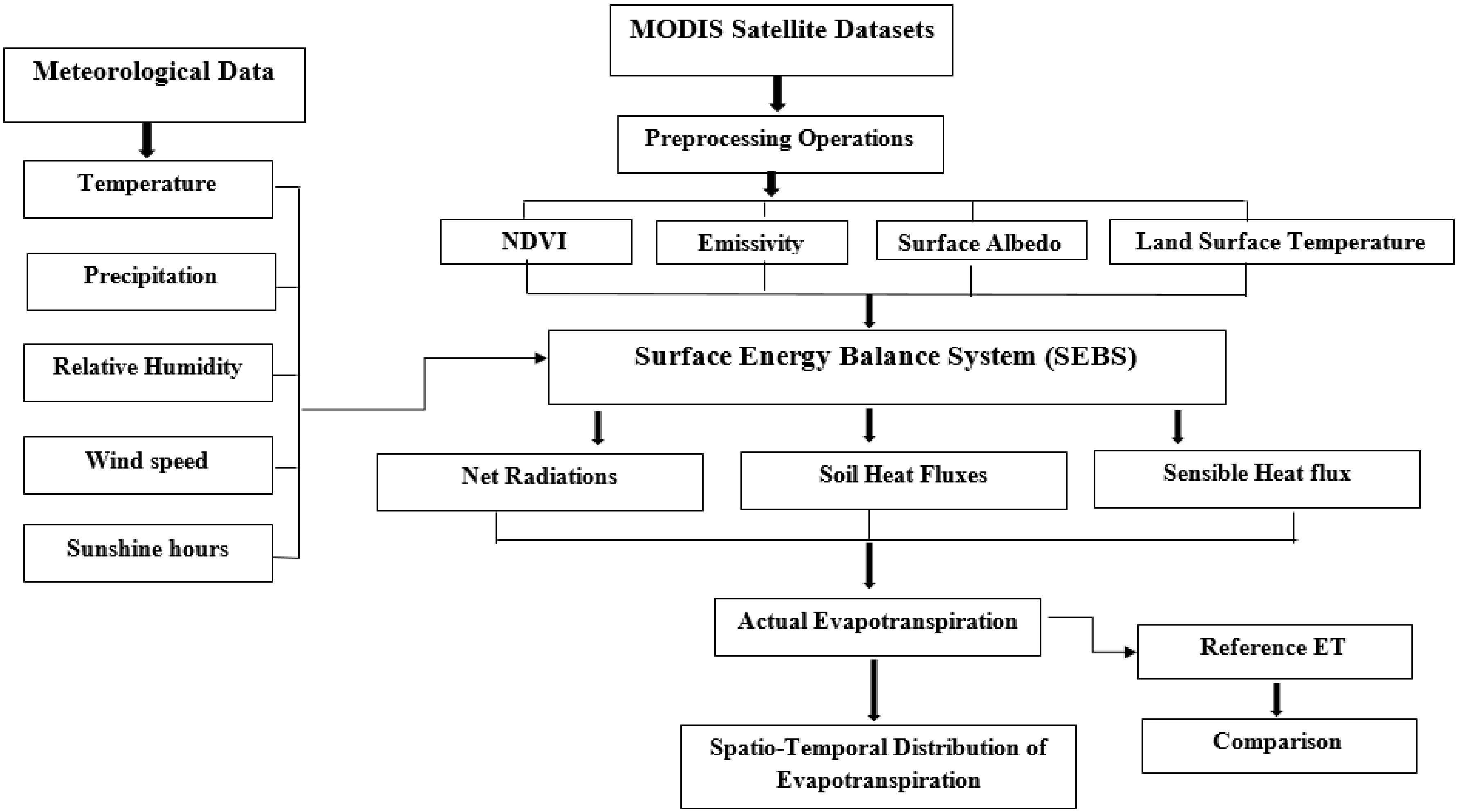

Figure 3.5. Methodology Flowchart

3.3. Data Pre-Processing

In preprocessing each required layer of various parameters like land surface temperature, surface emissivity, surface albedo, leaf area index and NDVI values were derived from the specific bands using MODIS Reprojection tool (MRT) and converted into geographic coordinate system and subset according to study area.

3.3.1. Image Calibration

The remotely sensed imagery used for the research work have gone through radiometric and geometric corrections. In radiometric correction the satellite images were converted from Digital Numbers into Radiance and then to Reflectance. The calibration of sensor is essential when images from multiple sensors or time series are to be used and when important parameters like reflectance and temperature are required. Thus DN must be converted to radiances or reflectance, by using calibration offset and gain coefficient for each spectral band

3.3.1.1 Radiance

Radiance is the outgoing radiation observed at top of atmosphere by the satellite and measured in $W/m^2/sr/\mu m$. It is calculated as follows.

$$L\lambda = Lmax - Lmin / \ Qcalmax - Qcalmin \times (DN - Qcalmin) + Lmin \quad (3.1)$$

Where

- DN is the digital number of each pixel,
- Lmax and Lmin are calibration constants, and
- Qcalmax and Qcalmin are the highest and lowest range of values for rescaled radiance in DN

3.3.1.2. Reflectance

Reflectance is the ratio of incident radiation to the reflected radiations. It is calculated as follows.

$$P\lambda = \pi * L\lambda \, / \, ESUN\lambda * \cos\Theta * dr \qquad (3.2)$$

Where

- $L\lambda$ is the spectral radiance for each band
- ESUN λ is the atmospheric radiance of bands ($W/m^2/\mu m$)
- θ is the cosine of the solar incidence angle
- dr is the inverse squared relative earth-sun distance

3.4. Biophysical Parameters

SEBS needs several biophysical parameters to be estimated from image bands including vegetation indices, surface albedo, surface emissivity, land surface temperature. These parameters were calculated as follows.

3.4.1. Vegetation Indices

Among the various vegetation indices, Normalized Difference Vegetation Index (NDVI) is the most common. MODIS vegetation indices product can be useful for the monitoring of temporal changes along with global evaluation of vegetation conditions. Vegetation indices can also be useful as a parameter for evaluating global and regional climate and hydrologic processes.

In this study NDVI was calculated as follows.

$$NDVI = (NIR - RED) \, / \, (NIR + RED) \qquad (3.3)$$

3.4.2. Land Surface Temperature and Emissivity

The satellite images and the associated thermal bands radiance help in calculating the Land surface temperature. The surface emissivity is ratio of the actual radiations to the total radiation emitted by at the same surface temperature. The LST and emissivity data layers along with data quality (QC) information layers were extracted from bands and projected from native sinusoidal projection to geographic projection.

3.4.3. Surface Albedo

Surface albedo is ratio between the amounts of reflected radiations to the incident radiations. Surface albedo is calculated with the help of information on spectral radiance using shortwave bands.

3.4.4. Leaf Area Index (LAI)

The variable Leaf Area Index (LAI) is described as the ratio between leaf areas to ground beneath it. It is used as satellite-derived parameter for the estimation of vegetation content for evapotranspiration and net primary production. The leaf area index values for a variety of land cover are vital for appropriate modeling energy budget components for specific catchments.

3.5. Determination of Sensible heat flux

The SEBS model uses the similarity theory for calculating the sensible heat flux. The sensible heat flux is the rate of heat that is lost to atmosphere by the process of convection and conduction. It requires cautious consideration of ground conditions, land use and require ground observations of wind speed, precipitation and air temperature.

$$H=\rho air * Cp\ dT/ rah \qquad (3.4)$$

Where,

- ρair is air density (kg/m3),
- Cp is air specific heat (1004 J/kg/K),
- dT (K) is the temperature difference (T1 – T2) between two heights (z1 and z2), and
- rah is the aerodynamic resistance to heat transport (s/m) between heights.

The aerodynamic resistance is based on neutral stable atmospheric conditions where friction velocity is computed as;

$$u^* = kux / \ln (zx\ zom) \qquad (3.5)$$

Where

- ux is wind speed (ms^{-1}) at a blending height zx (first calculated as constant for z=200 m as constant for neutral conditions)
- Zom is momentum roughness length (m). The friction of air that interconnects with the surface calculated as 0.018×LAI in agricultural areas.

3.6. Soil Heat Flux

Soil heat flux (G) is defined as the amount of heat stored in soil and vegetation. It is one of the components of the energy balance equation. This energy flux enters the land surface during the day and exits the land surface at night. Generally, the soil heat flux is assumed to be zero over a 24-hour period (Muhammed, 2012). It is calculated as follows

$$G/Rn = (Ts-273.15)\ (0.0038+0.0074\alpha)\ (1-0.98NDVI) \quad (3.6)$$

Where,

- Ts is the surface temperature (K), and
- α is the surface albedo.

3.7. Net Radiation

Rn the net radiations is the radiation available at the land surface, the difference between net gains and losses and is calculated as follows

$$Rn = RS\downarrow - \alpha\ RS\downarrow + RL\downarrow - RL\uparrow - (1-\varepsilon o)\ RL\downarrow \quad (3.7)$$

Where;

- $RS\downarrow$ is the incoming shortwave radiation (W/m2),
- α is the surface albedo (dimensionless),
- $RL\downarrow$ is the incoming long wave radiation (W/m2),
- $RL\uparrow$ is the outgoing long wave radiation (W/m2), and
- εo is the surface thermal emissivity (dimensionless).
-

3.8. The evaporative fraction

To determine the evaporative fraction; Su (2002) used Equation Hwet = Rn – Go - λEwet and Penman equation. The equation to determine the latent heat energy can be given by equation 3.8 as follows:

$$\lambda E = [\Delta \text{ x re x } (Rn - Go) + pcp\ (es - ea)] / [re\ (\gamma + \Delta) + \gamma \text{ x ri}] \quad (3.8)$$

Where Δ is the rate of change of saturated vapor pressure with temperature ($hPaK^{-1}$); re is aerodynamic resistance ($s.m^{-1}$); es is saturated vapor pressure (hPa); ea is actual vapor pressure (hPa); γ is the psychometric constant($hPa.K^{-1}$) and ri is the bulk surface internal resistance ($s.m^{-1}$).

3.9. Estimation of Evapotranspiration.

The latent heat flux expresses energy as the vapor flux to the atmosphere. Actual ET was then calculated by Equation 3.9

$$ET = \lambda E / \rho w.\lambda \quad (3.9)$$

Where ET is the evapotranspiration in water depth [$mm\ s^{-1}$], and ρw is the density of water [$kg\ m^{-3}$].

Evapotranspiration was originally in [$mm.sec^{-1}$] as satellite images provide an instantaneous observation in time. Evaporative fraction was therefore used for determination of daily evapotranspiration, assumed that evaporative fraction remains constant throughout the day (Lu et al., 2012). Total daily evapotranspiration was estimated by following equations

$$Edaily = \Sigma\ [\Lambda.\ Rn - Go/\rho w.\lambda] \quad (3.10)$$

$$= 24(h).3600(s).\ [\Lambda.\ Rndaily - Godaily\ \rho w.\ \lambda]$$

$$E_{daily} = 8.87 \times 107. [\Lambda. Rn_{daily} - Go_{daily} \rho w.\lambda]$$

where E_{daily} is the evapotranspiration for a day [mm day $^{-1}$], Rn_{daily} is the average daily net radiation, Go_{daily} is the daily soil surface heat flux, , λ is the latent heat of vaporization [J kg^{-1}] with a value of 2.47×10^6.

The assumption made is that the daily soil heat flux is approximately equal to zero since the downward flux in daytime is balanced by the upward radiations at night. Therefore only daily net radiation flux is required for the calculation of daily evaporation given by equation 3.11

$$Rn_{daily} = (1-\alpha).Rswd24 + \varepsilon\ Rlwd24 \qquad (3.11)$$

Rswd24 is the daily downward short wave radiation and Rlwd24 is daily net long wave radiation (Su, 2002).

Chapter 4

RESULTS AND DISCUSSIONS

4.1. Spatio-Temporal pattern of Evapotranspiration

The Evapotranspiration for the calendar years 2001-02 and 2015-16 have been estimated with the help of surface energy balance system (SEBS) model using MODIS satellite data and Meteorological data obtained from Pakistan Meteorological Department. After analyzing the results of evapotranspiration maps a large variations in the evapotranspiration has been observed in the canal command areas of Jhelum and Chenab and these variations can mainly be attributed to the changes in crop growth pattern and climatic parameters such as temperature, precipitation The Spatio-temporal distribution maps of evapotranspiration are shown in the Figure 4.1 below.

The study area is covered by agriculture crops mainly wheat-rice rotation, other crops found are sugarcane, cotton and maize. The water requirement is fulfilled by surface water mainly provided through the network of canals to optimize the soil moisture and increase the productivity. The Fig 4.1 showing the evapotranspiration maps reveal that maximum evapotranspiration has been observed in the summer season mainly in May. The highest temperature has been recorded in May followed by low precipitation. The days in summers are long, hot exhausted and results in increase in evapotranspiration. The ET values have slightly decreased in July because of peak monsoon precipitation and the temperature has slightly dropped due to increase in precipitation. Another reason for a slight drop in the ET is the increase in the humidity values during the peak monsoon season. The evapotranspiration values have gradually decreased over the months and the lowest values have been observed in the winter season mainly in January around 1.1 mm.

The reason is the drop in the temperature values along with the low soil moisture condition due to low precipitation in winter season. The results have revealed that evapotranspiration is highly sensitive to the variations in the temperature. The ET values are lowest in January but in areas where the wheat crop is in emerging stage the values are comparatively higher. The Rabi season starts from November and continues till April. The major crop in the Rabi season is wheat. The north-eastern areas like Gujranwala, Hafizabad and Sheikhupura are wheat dominant areas. The wheat crop's sowing begins in late November and then the initial growth starts in December. In these areas the ET values are slightly higher because the wheat crop is emerging.

During the kharif season, which starts from late April and continues till October rice is grown in the north-eastern areas of Gujranwala, Hafizabad and Sheikhupura. The rice crop is generally grown in standing water. The ET values in these areas are much higher because evapotranspiration from standing water is higher as compared to barren land or other dry areas. The Fig 4.2 has showed that evapotranspiration values have increased in the year 2015-16. The increase of evapotranspiration values years can be mainly attributed to the increase in the temperature According to the meteorological data the temperature has increased from 0.40^{0}C to 0.90 ^{0}C during present decade. This has resulted in the increase in the ET values. In the year 2015-16 the ET values start increasing from March. The maximum evapotranspiration values have been observed during the pre-monsoon season which are around 6.1 mm. This season starts from mid-April to June with hot short nights and long exhausted days with overall high temperature. During the monsoon season mainly in July maximum precipitation has been observed around 250mm.

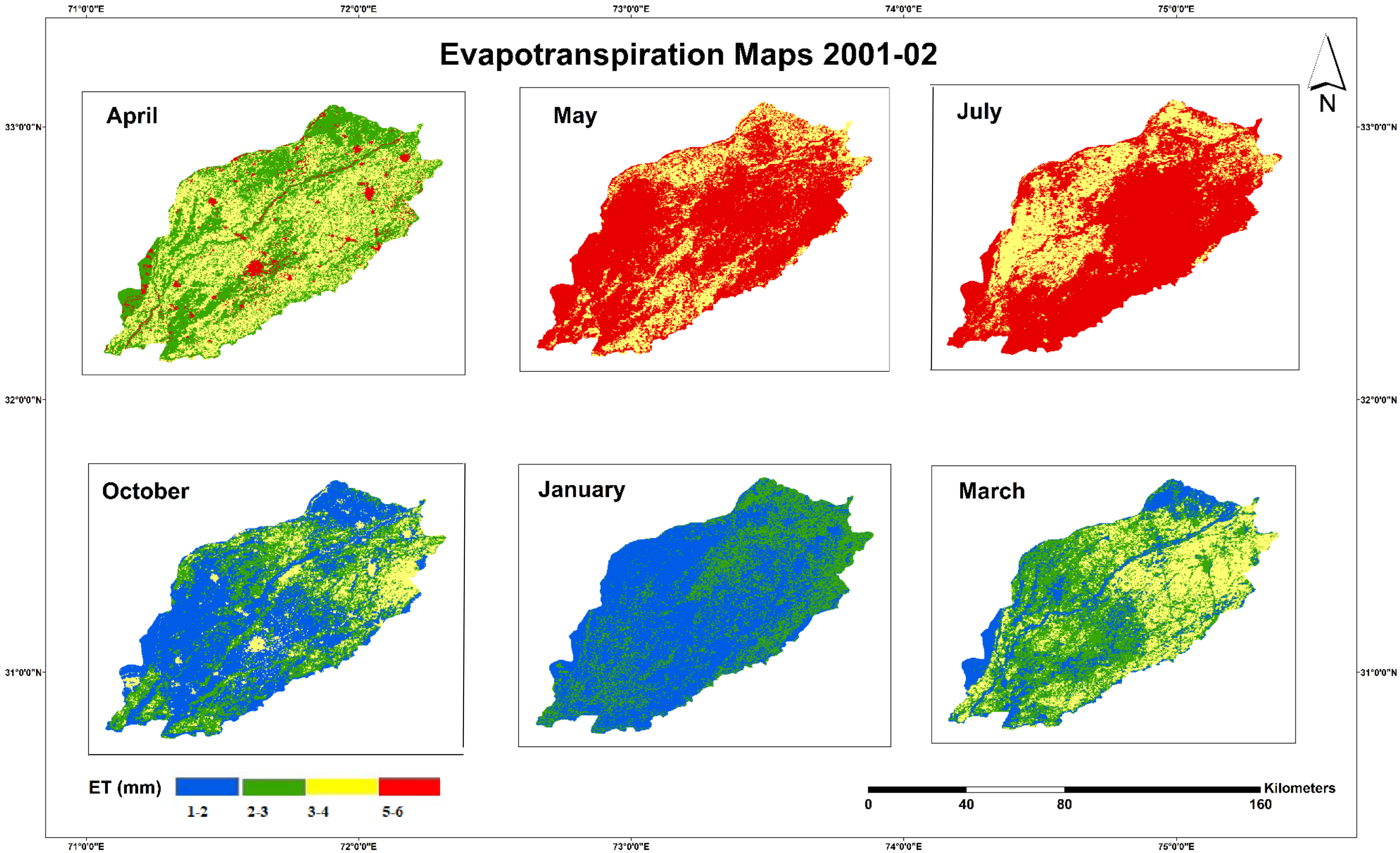

Figure 4.1. Maps showing the distribution of evapotranspiration.

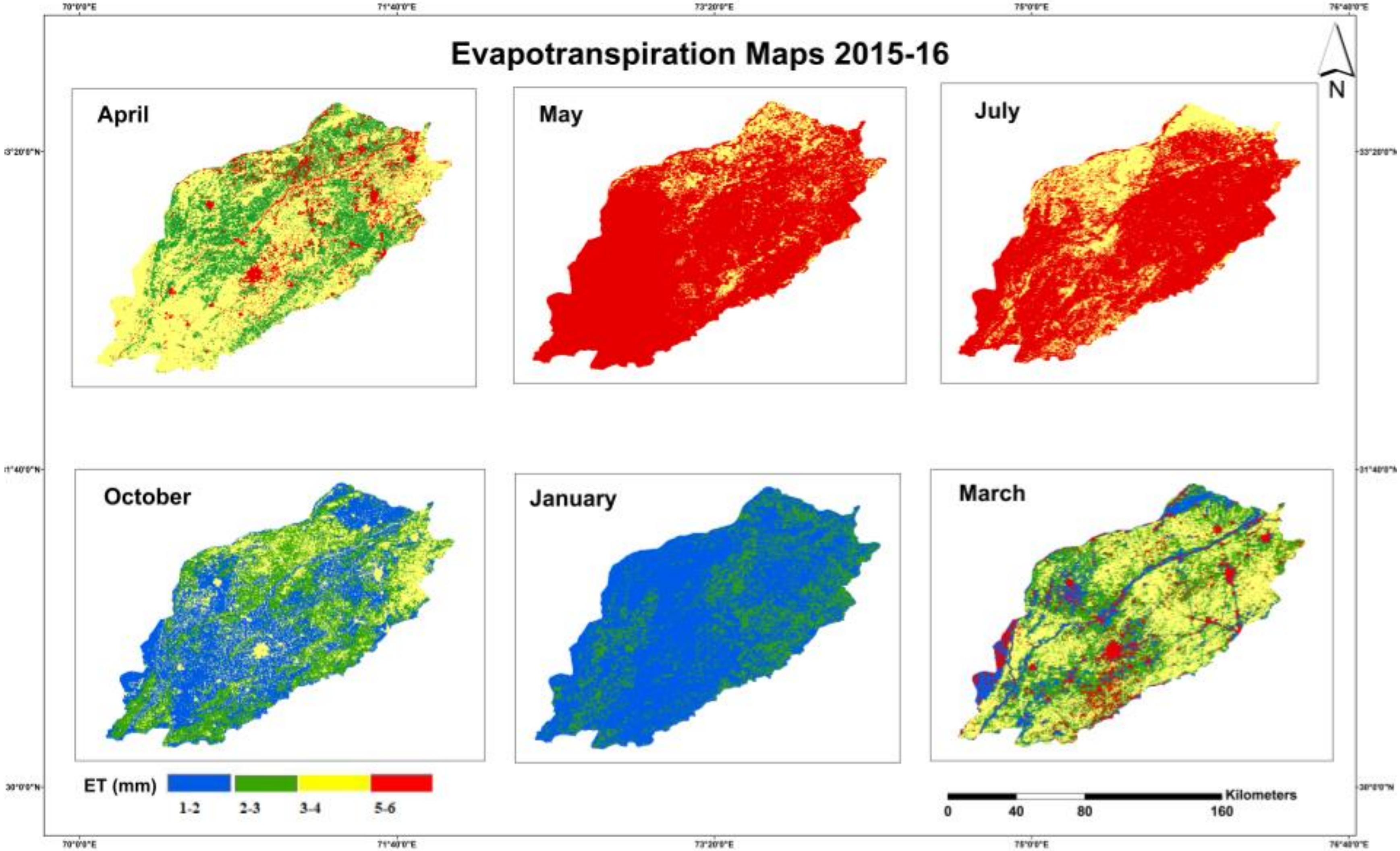

Figure 4.2. Distribution of evapotranspiration in year 2015-16

The results of the present study has concluded that summer and spring ET has large spatial variations than autumn and winter ET. This is due to larger variations in temperature, humidity and precipitation values over the canal command areas. The evapotranspiration has increased in the recent years mainly during the months of summers due to peak temperature. The values have gradually decreased over the months and in winters the trend remains almost similar as shown in Figure 4.3, a slight increase in the values have been observed again in February and march. In the March the ET values start increasing further due to the increasing temperature and maturity stage of wheat.

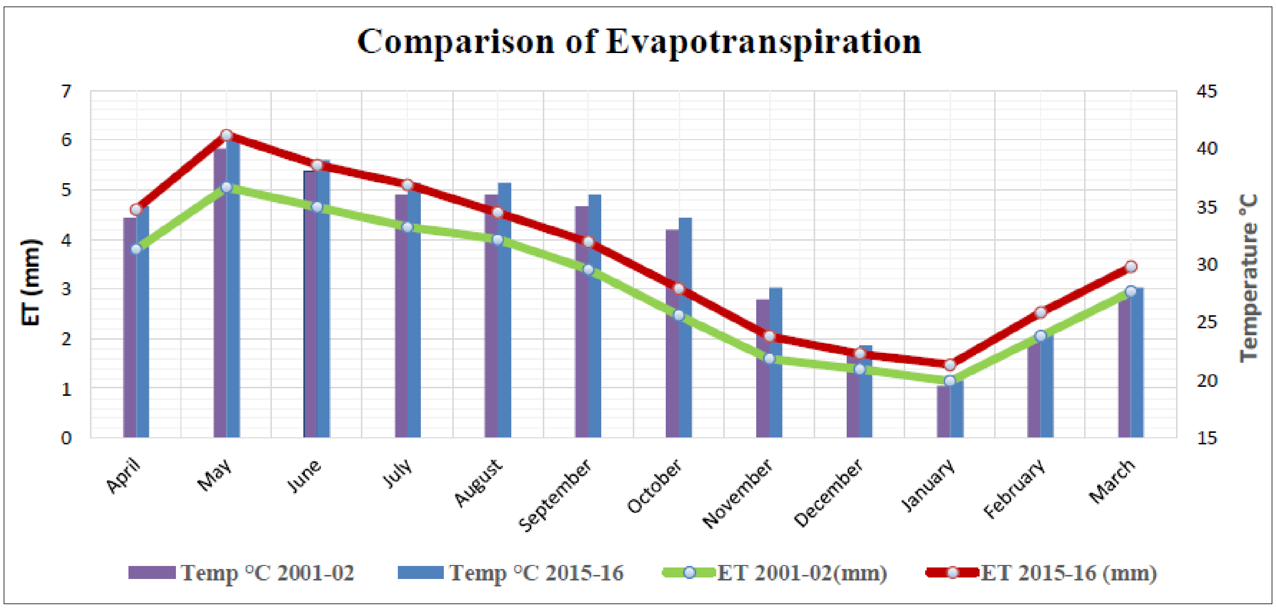

Figure 4.3. Comparison of evapotranspiration.

Table 4.1. Evapotranspiration values for years 2001-02 and 2015-16

Months	ET 2001-02 (Mean mm/month)	ET 2015-16 (mm/month)
April	3.8	4.6
May	5.05	6.1
June	4.65	5.5
July	4.25	5.1
August	4.01	4.54
September	3.4	3.95
October	2.47	3.01
November	1.6	2.05
December	1.39	1.7
January	1.15	1.48
February	2.05	2.53
March	2.93	3.45

4.2. Validation of SEBS based ET with Reference ET_O.

For the purpose of validation the SEBS estimated evapotranspiration values that geographically corresponded to the regional agro-met station Faisalabad were extracted and compared. The evapotranspiration values computed from surface energy balance system (SEBS) model were plotted against the reference evapotranspiration ET_O values calculated using FAO-56 Penman Monteith equation. The reference ET at the agro-met station has been compared with the pan evaporation method as well. A reasonably strong correlation was found, yielding coefficients of determination (R^2) of 0.87 (Figure 4.4). Generally, the evaluation has shown that SEBS model has calculated the evapotranspiration fairly well.

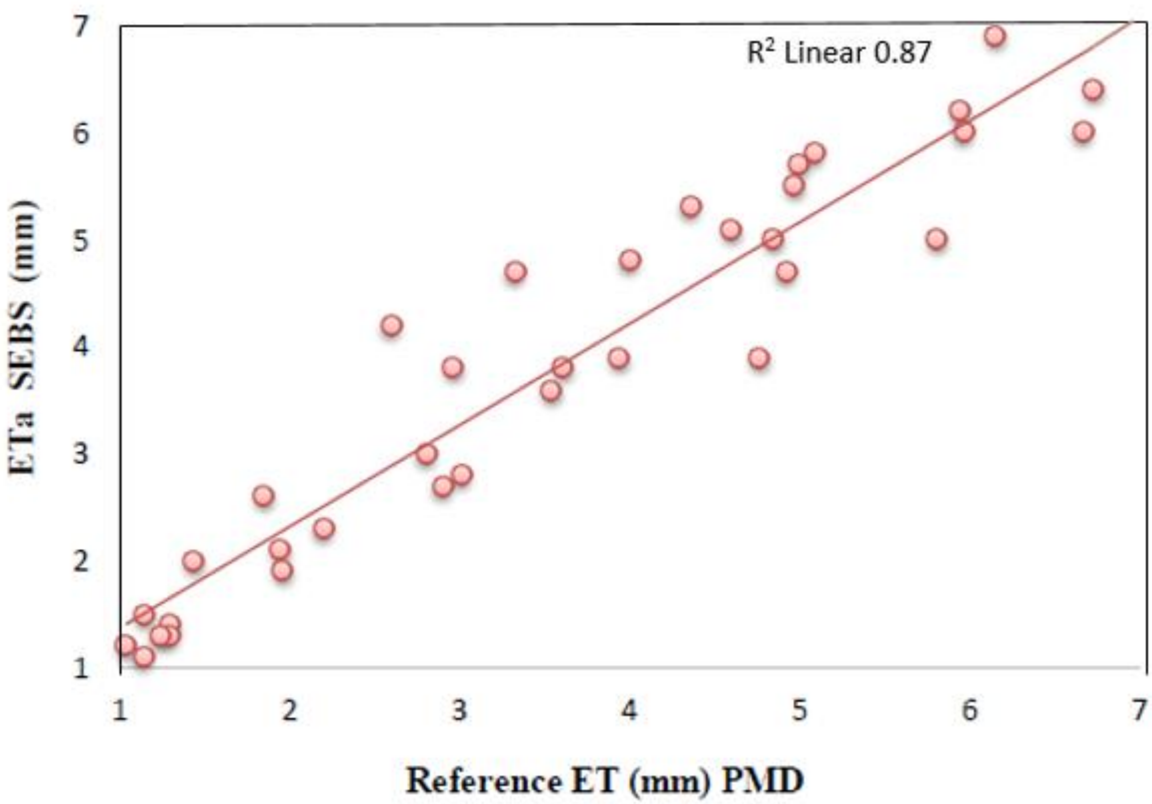

Figure 4.4. Comparison between Reference ETo and SEBS ETa

4.3. Effect of Climatic and Biophysical Variables on Evapotranspiration.

The Pearson correlation and linear regression were performed between evapotranspiration and different climatic and biophysical variables to determine the quantitative effect of these variables on the estimated evapotranspiration. Among climatic variables temperature, relative humidity, sunshine hours and wind speed were compared against the evapotranspiration values whereas, biophysical variables involved NDVI and albedo.

4.3.1 Evapotranspiration and Temperature.

The scatter plot comparison between Evapotranspiration and Temperature values has been shown in Fig 4.5. A strong positive correlation has been found between Temperature and ET values. The ET is highly sensitive to the variations in the temperature and has gradually increased with an increase in Temperature mainly during the summer season. Statistical measures like Pearson R indicate a strong value of 0.88 while Coefficient of Determination R^2 has a value of 0.80 and results are statistically significant at the 0.05 probability level.

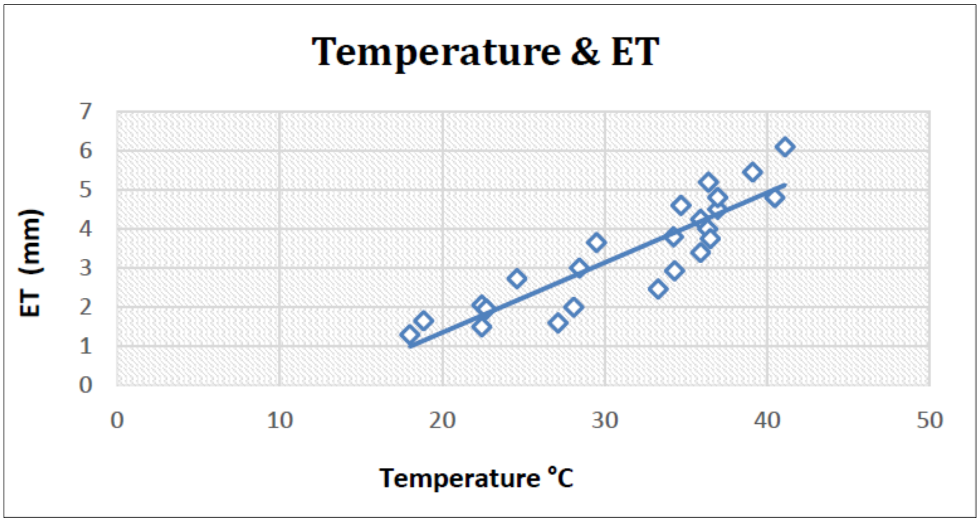

Figure 4.5. Comparison between Evapotranspiration and Temperature values

4.3.2. Evapotranspiration and humidity.

The relationship between Evapotranspiration and humidity has been shown in Fig 4.6. Negative relationship was found between the ET and humidity values. The rate of evaporation at a given place is always dependent on the humidity of that place because if the air is already filled with water vapors, it will not have any space to hold excess water vapors and the incoming solar radiations will also be absorbed due to the presence of water vapors therefore, evaporation will occur at an extremely slow rate. More humid the air, more water vapors it contains. The statistical analysis have revealed Pearson R -0.60 and Coefficient of Determination R^2 0.30 and results are statistically significant at the 0.05 probability level.

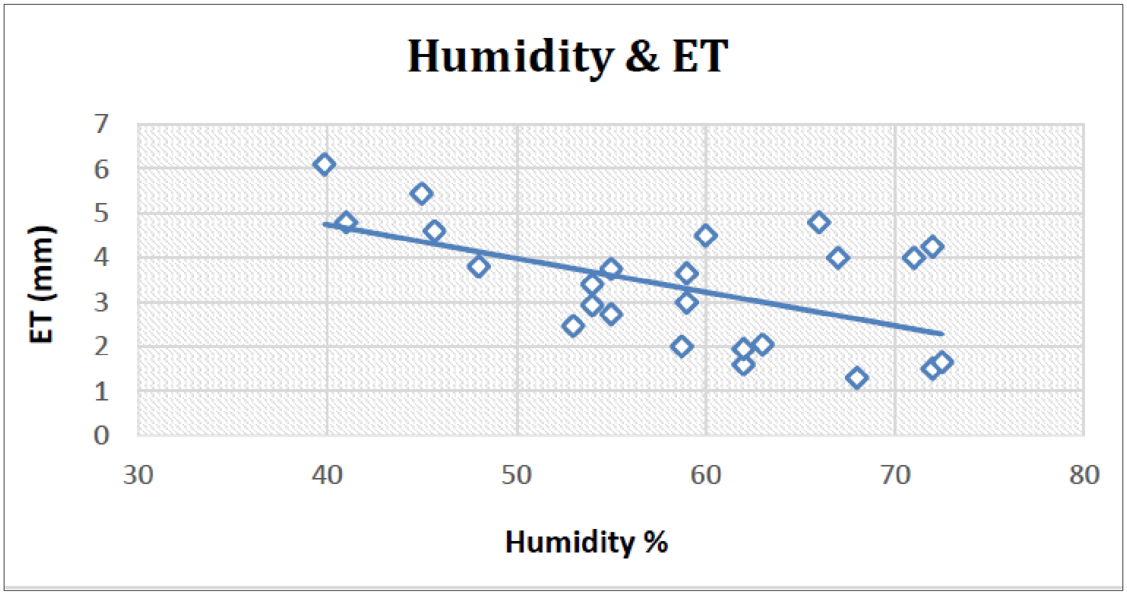

Figure 4.6. Comparison between Relative humidity and ET

4.3.3. Evapotranspiration and wind.

The wind speed affects the rate at which the water evaporates. Increase in wind speed helps in transferring the moisture filled air to other places, hence bringing dry air which can absorb more water. The wind creates room for extra water vapor and evaporation will continue to occur. The statistical measures like Coefficient of Determination R^2 indicate a low value of 0.37. The overall contribution is less as compared to temperature & Humidity (Figure 4.7). If the humidity present at a particular place is more than the increase in the wind speed can help to transfer the air to other places and the fresh air with less moisture would then be able to replace it.

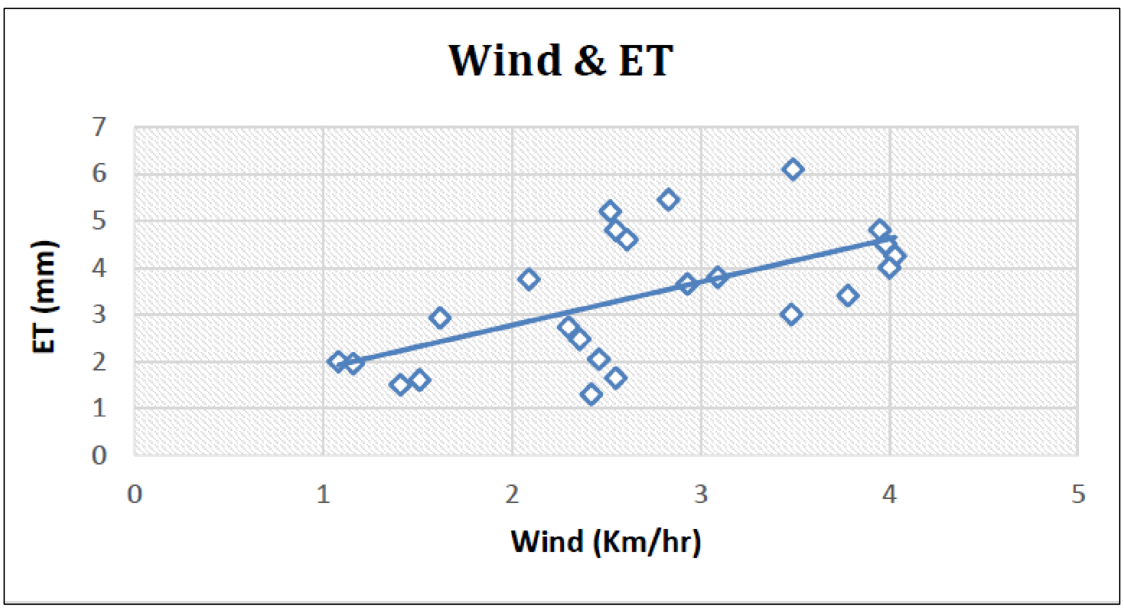

Figure 4.7. Relationship between Evapotranspiration and Wind.

4.3.4. Evapotranspiration and sunshine.

Heat from the sun, the solar energy, powers the evaporation process. Solar energy is the main driving force behind the hydrologic process. During the winter season the days are shorter with an average of less than 10 hours and solar radiations are less intense. While in summers the days are longer with an average of 12 hours and solar radiations are more intense. The increase in the sunshine hours can fuel the process and results in higher evapotranspiration values. The results of the statistical analysis has revealed Pearson R value of 0.65 while Coefficient of Determination R^2 has a value of 0.40 and the results are statistically significant at the 0.05 probability level as shown in figure 4.8.

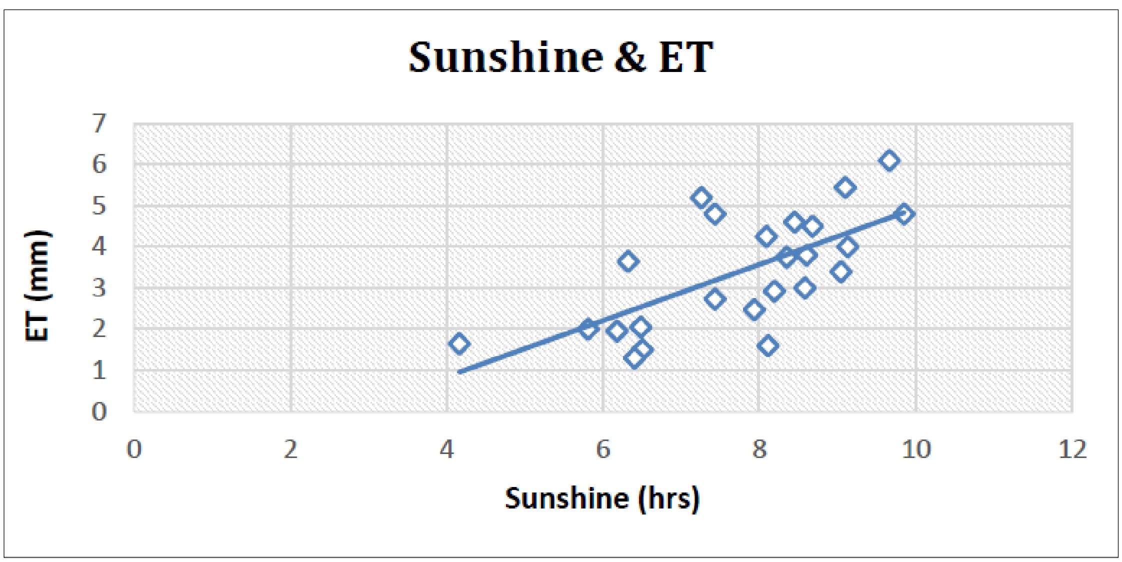

Figure 4.8. Comparison between Evapotranspiration and Sunshine hours.

4.3.5. Evapotranspiration and Normalized difference vegetation index (NDVI)

The relationship between evapotranspiration and NDVI values has been analyzed. These two variables are negatively correlated as shown in the Figure 4.9. The sowing of the wheat crop begins in late November during Rabi season. The NDVI values gradually increase as the wheat crop starts growing during the winter season mainly in December and January. The Evapotranspiration values during winter season and in the month of January are lowest due to low temperature values. The maximum values of NDVI 0.7-0.8 are found close to the maturity stage of wheat. After harvesting the NDVI values drops while the Evapotranspiration starts increasing due to the summer season and the increase in the temperature.

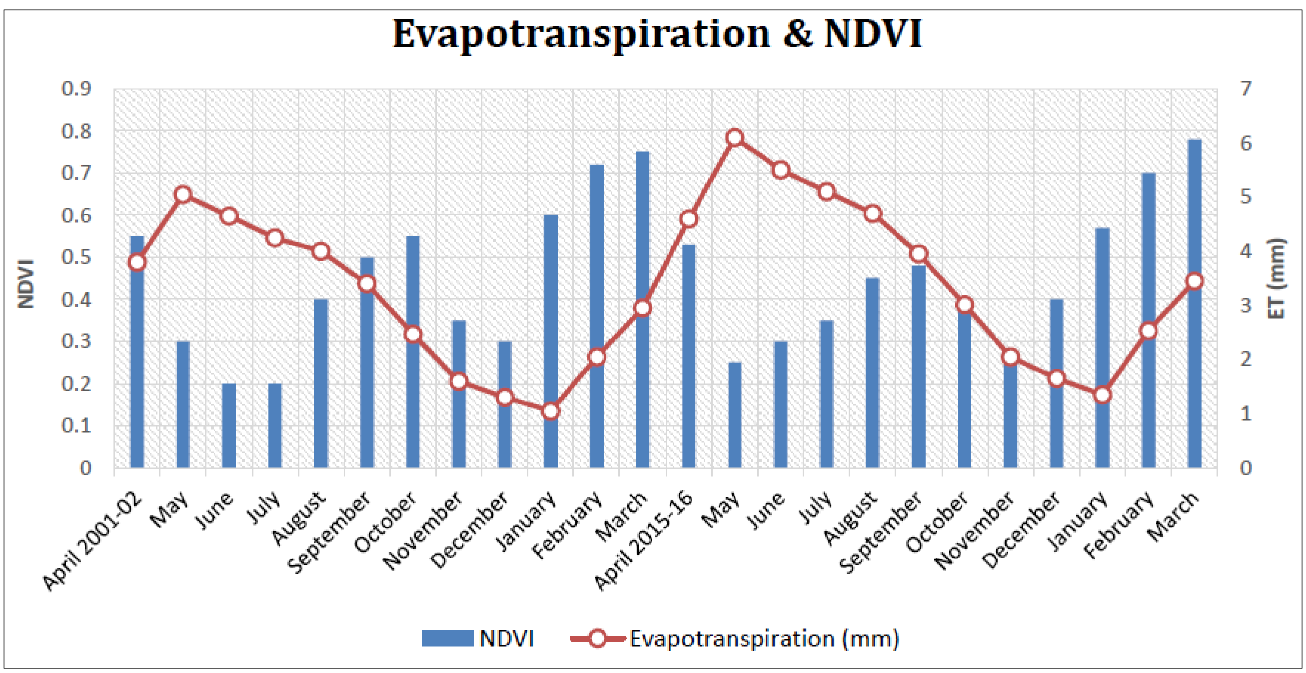

Figure 4.9. Relationship between Evapotranspiration and NDVI

During the monsoon season the NDVI values are lowest due to standing water in the canal command areas as the rice crop is sown during this season. The NDVI values are lowest values in water while the evaporation in dominant during these months. So the comparison between the NDVI and evapotranspiration has revealed that the two variables are negatively correlated with a Pearson R value of - 0.37 while Coefficient of Determination has value of R^2 0.15 (Figure 4.10). The results are not statistically significant in this case ($P<0.05$).

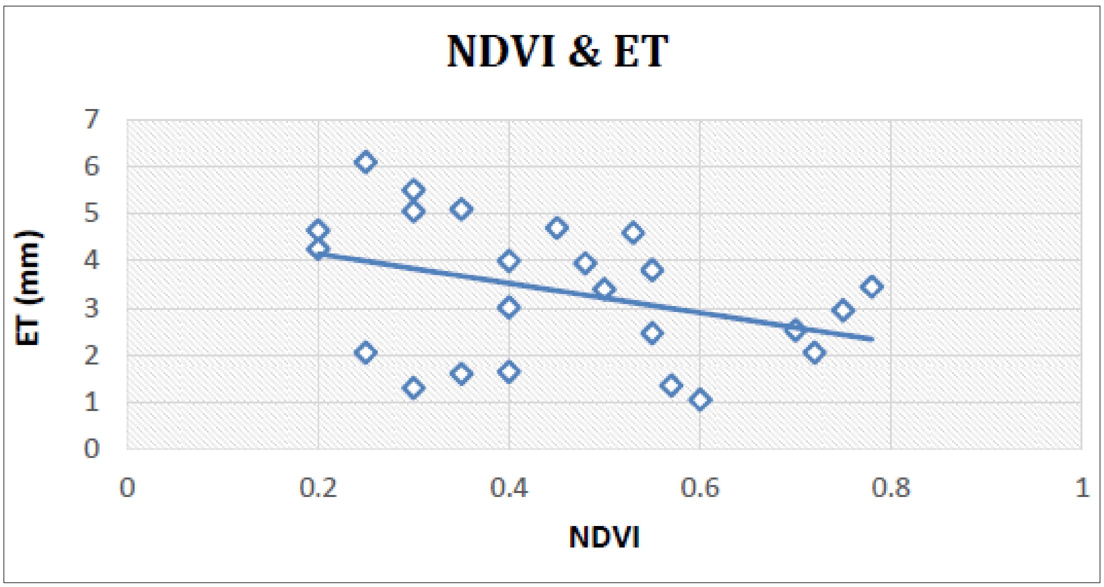

Figure 4.10. Scatterplot between NDVI and ET

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusion

The estimation of Evapotranspiration is very important for efficient irrigation practices, fulfilling the crop water requirements and monitoring water use over time. There are complex land-atmosphere interactions and there is natural variability in topography, soil moisture, climate and other biophysical parameters which collectively make the estimation of evapotranspiration very difficult. The issue is further intensified in water scarce countries like Pakistan having Arid to semi-arid climate. The traditional techniques available for estimation of ET provides measurements over small areas and the process is very hectic, time consuming and expensive. The satellite remotely sensed data provides large area coverage with high spatial and temporal frequency. The estimation of ET is vital for hydrological, agricultural and environmental purposes in a developing country like Pakistan where its economy is mainly dependent on agriculture and agriculture sector is the main consumer of water.

The Surface energy balance system has been successfully used for estimation of evapotranspiration in Jhelum and Chenab canal irrigation system with the help of MODIS datasets and Meteorological parameters obtained from Pakistan meteorological department. The canal command areas have mixed cropping pattern with rice, cotton as the major crops during the wet kharif season and wheat as the dominant crop during the dry Rabi season. Mainly there is wheat-rice rotation in the study area.

The evapotranspiration has changed seasonally due to climate and cropping patterns. The ET of all the crops follow a pattern, low evapotranspiration during the early stage of crop growth, maximum close to the maturity stage and then the ET declines after the harvesting. During the recent years overall evapotranspiration values have increased in the canal command areas which can be mainly attributed to the increase in the temperature values. According to the meteorological data the temperature has increased from 0.40 to 0.80 ^{0}C during the recent decades. The increasing evapotranspiration rate may lead to a severe shortage of irrigation water that can have harmful effect on the crop growth and will have impact on the national economy as well. The surface energy balance algorithm (SEBS) is capable of estimating Evapotranspiration fairly well (R^2 0.87) as compared to the Reference ET obtained from Pakistan Meteorological department at Agro-Met station. Among the various climatological elements, temperature followed by wind & sunshine significantly ($P<0.05$) impacted the evapotranspiration values, whereas relative humidity has shown a negative trend.

5.2. Recommendations

In order to address and mitigate water scarcity concerns at a national level, there is a need to consider the socio-economic factors. For the improved long-term and sustainable management of irrigation water supply, the evaporation estimation at fine resolution is required. The field based estimated data of ET using Lysimeters or Scintillometer in the canal command areas should be available for validation of results. The water management policy in Pakistan must take advantage of the remote sensing techniques to avoid severe water scarcity in the near future. The precision agricultural technologies are required in Pakistan along with high efficiency drip Irrigation techniques, these would help the policy-makers to plan effective irrigation measures towards the sustainable development in Pakistan.

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