Estimation and Mapping of Solar Radiation, Net Radiation and Reference Evapotranspiration Over Kathmandu Valley

A DISSERTATION
Submitted to Central Department of Environmental Science
In partial fulfillment of requirements of Masters Degree in Environmental Science

SUBMITTED BY:
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2006

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TRIBHUVAN UNIVERSITY

(Institute of Science and Technology)

CENTRAL DEPARTMENT OF ENVIRONMENTAL SCIENCE

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Central Department of Environmental Science
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LETTER OF RECOMMENDATION

This is to certify that the dissertation report entitled "**Estimation and Mapping of Solar Radiation, Net Radiation and Reference Evapotranspiration Over Kathmandu Valley"** being submitted to Central Department of Environmental Science, T. U., Kirtipur, Nepal by Mr. Suman Bajracharya in partial fulfillment of the requirement for the completion of Masters degree in Environmental Science is a bonafide record of work carried out by him under my supervision and guidance.

The results presented in this dissertation are original and has not been accepted for any other degree. I, therefore, recommend his work for the approval.

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....

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Kirtipur

LETTER OF APPROVAL

This dissertation prepared by Mr. Suman Bajracharya entitled "**Estimation and Mapping of Solar Radiation, Net Radiation and Reference Evapotranspiration Over Kathmandu Valley"** has been accepted as a partial fulfillment of the requirement for the completion of Masters Degree in Environmental Science.

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ABSTRACT

Evapotranspiration data are important in many agricultural and engineering applications. There are many empirical formulas to compute Evapotranspiration. Penman-Monteith method is considered as the best method to estimate reference crop evapotranspiration. To estimate reference evapotranspiration using the P-M method, weather parameters such as air temperature, humidity, wind speed, solar radiation, and net radiation are required. But, all these climatic parameters required are not measured at all the rainfall stations. Therefore, these parameters are estimated using climatic models based on the generally measured climatic parameters. Out of these parameters, Solar and Net radiation are the parameters do not available easily, but can be estimated from sunshine hours or cloudiness. In this study, the estimation of solar radiation, Net radiation and Reference Evapotranspiration for all the seventeen selected locations in the Kathmandu valley watershed has been carried out using the guidelines and reliable relations reported by Allen et. al. (1998).

This current study provides derived data of the inputs parameters as well as that of Solar radiation, Net radiation and Reference ET. The derived data have been compared with some ground-measured data and has shown good agreement, with differences generally fewer than 10 per cent. Solar Radiation ranges from 154.88 W/m^2 in December to 250.77 W/m^2 in April. Net radiation ranges from 34.61 W/m^2 in December to 116.59 W/m^2 in May.

Mean daily solar radiation values at selected locations are barely different. However, mean daily radiation above south facing slopes of northern part of Kathmandu valley watershed was consistently higher than that above the northern slope of southern hills. The average annual Referenced ET is estimated to be 886.20 mm. More ETo has been observed in the sun-facing surfaces than the surface opposite to sun. Daily values of solar, net radiation and ETo for each month provide the information of energy and radiation balance and water balance in Kathmandu valley.

Again, these three variables are mapped. Elevation as well as latitude and longitude were used as explanatory variables to take into account the variation of all the parameters. The Reference ET estimates at 17 stations were interpolated to give gridded values. For each variable, there is one mean annual map and twelve mean monthly maps. The estimating methods, data and maps of solar radiation, net radiation and ET, are recommended to use in many environmental fields.

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ABBREVIATIONS

CDHM	Central Department of Hydrology and Meteorology
DHM	Department of Hydrology and Meteorology
E	Evaporation
ET	Evapotranspiration
ETo	Reference Evapotranspiration
FAO	Food and Agriculture Organization
GIS	Geographic Information System
HMG/N	Government of Nepal
ICIMOD	International Centre for Integrated Mountain Development
IUCN	The World Conservation Union
IWMI	International Water Management Institute
Ktm	Kathmandu
kPa	Kilo Pascal
KV	Kathmandu Valley
LRMP	Land Resource Mapping Project
m	Meter
MJ	Mega Joule
PE	Potential Evaporation
PET	Potential Evapotranspiration
PM	Penman Monteith
P-M	Penman-Monteith
REF-ET	Reference Evapotranspiration
RH	Relative Humidity
s	Second
Stn.	Station
TU	Tribhuvan University
VDC	Village Development Committee
VPD	Vapour Pressure Deficit
w	Watt
WMO	World Meteorological Organization

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CHAPTER ONE

1. INTRODUCTION

1.1 BACKGROUND

Evapotranspiration (ET) is a collective term for the transfer of water, as water vapor, to the atmosphere from both vegetated and bare land surfaces. It is affected by climate, availability of water and vegetation. ET is a large component of the water balance; over the entire land surface of the globe, rainfall averaged around 750 mm per year, of which some two thirds is returned to the atmosphere as evapotranspiration (Baumgartner & Reichel, 1975 cited in Wallace, et.al. 1993). About 62% of continental precipitation evapotranspires; about 97% of this is from land and 3% from open water bodies. Evapotranspiration represents nearly all the soil and surface water loss from dry environments, where runoff is minimal. The combination of two separate processes, whereby water is lost on one hand from the soil surface by evaporation and on the other hand from the vegetation by transpiration, is referred to as evapotranspiration (ET) [FAO, 1998]. Both soil evaporation and plant transpiration represent evaporative processes. Evapotranspiration data are usually presented as a depth of water loss over a particular time period in a manner similar to that of precipitation. Common units for ET are inches/day or millimeters/day.

A large number of hydrologic rainfall/runoff and water quality models include ET as one of the primary input variables. ET is one of the important parameters in calculating Crop Water requirements and irrigation water requirement. Estimation of evapotranspiration is needed to support irrigation design and scheduling, watershed hydrology studies, process-based crop growth models, and other models that attempt to simulate the soil water budget. The estimation of ET is also a critical part in the water accounting process (Moldel, 1997 as cited in Shilpakar, 2003).

However, despite its importance, ET is difficult to measure or observe directly at a meaningful scale in space or time. Surrogate measures, such as evaporation from the US Class A evaporation pan, have been used. In most of the hydrologic water and nutrient budgets, ET is calculated based on the potential evaporation (PE) or reference evapotranspiration (ETo), a term synonymous to potential ET (PET) for a reference crop or vegetation (Jensen et al., 1990; Amatya et al., 1995 as cited in Amatya et. al., 2000).

Evapotranspiration is estimated based on the climatic parameters recorded in the representative station and extrapolated for the larger area or can be computed as residual term in water balance. New technologies and technique of remote sensing improve the estimates of evapotranspiration at different spatial scale.

Estimates of ET can be obtained by using measured meteorological variables in mathematical equations to predict monthly or daily values. The equations or models vary from simple empirical relationships to complex methods based on physical processes such as the Penman-Monteith (1965) method (P-M method). The P-M method for estimating PET with reference to the characteristics and surrounding of the crop has been extensively studied with great success in a wide array of geographical and climatological conditions. It has been accepted as the best performing combination equation in the absence of measured PET data (Amatya et al., 1995; Jensen et al., 1990 as cited in Amatya et. al., 2000).

Although Penman Monteith model needs a lot of sophisticated meteorological data (Minimum Temperature, Maximum Temperature, Relative humidity, Wind speed and Sunshine hours) in recent time, it is considered to be the best. This crop weather model is adopted in most part of the world especially in Middle East. Egypt is a typical example country for it [FAO 1998]. Here, this study attempts to estimate Reference Evapotranspiration ETo based on the modified Penman and Monteith method for its very convincing performance under varying climatic conditions using the climatic models for the required meteorological data developed by TAHAL Consulting Engineers (2002) as cited in Nayava (2005). As the modified penman equation has been used extensively worldwide, the method has been taken as the main part of this thesis.

Solar radiation is an important weather variable for several agro-environmental studies. Solar radiation directly influences all the agriculture practices. Since evaporation and evapotranspiration requires continuous supply of energy which is derived mainly from solar radiation, the radiation will be a factor of considerable importance. 2.45 MJ energy is needed to vaporize 1 kg or 0.001 m^3 of water. The evaporation from a cropped soil is mainly determined by the fraction of the solar radiation reaching the soil surface. Solar energy provides the necessary energy for the evaporation either through the direct reflection on the plant and the soil or through the air heating and the circulation. Evapotranspiration is higher when there is no cloud and bright sunshine but lesser when there is no sun (cloudy). In the regions near the equator where the annual solar radiation is large the annual evaporation is also large.

Earth receives about 1/2000000000 of the sun‘s energy output. The amount of radiation intercepted by a surface at right angles to the solar beam at the outer limits of the atmosphere is approximately 1367 W/m^2 (1.97 calories per square centimeter per min.) and is known as the solar constant (Critchfield, 1999 & Oliver et. al. 2003). Much solar radiation data are available as a percent of available sunshine, or sunshine duration. The actual solar irradiance varies by 3.4% from the solar constant during the year due to the eccentricity of Earth's orbit about the Sun.

At the top of the Earth's atmosphere, insolation varies with latitude (it decreases toward the poles). At the Earth's surface insolation also varies according to dominant weather patterns. Regions that are typically always clear receive more insolation than regions that are frequently cloud-covered.

The number of ground-level weather stations recording daily radiation is very small compared to the number recording air temperature and precipitation. This could be a severe limitation for agricultural model applications. The need for solar radiation estimates at sites where it is not measured has grown in the past years. There have been great advances in the study of the distribution of solar radiation in different regions of the globe. However, there has been little attention on the distribution of radiation regime of the mountainous region.

The radiation regime of Nepal has been insufficiently studied. This is due both to the defects which must be compensated in organizing the observation, and to the comparatively complex theoretical investigation of the radiation fluxes under the conditions of mountain relief. Recognizing sun as a major natural resource of energy, with which Nepal is blessed in abundant measure, it is believed that solar energy is a valuable renewable source of energy that should be fully exploited for the benefit of the country.

Nepal has the potential to develop substantial Solar Power generation capacity as large, small and micro systems. With about 300 days of sunshine per year in most parts of the country and an average of eight light hours per day, it also has the potential of generation 3 – 4 kWh/ m^2 per day form solar energy, which was published by world energy council in its web site www.worldenergy.org.uk .

This study will try to map the solar radiation received as an auxiliary parameter for the estimation of Reference evapotranspiration using the modified Penman Monteith method. Thus, this thesis research is focuses on the estimation and mapping of ET and incoming solar radiation.

1.2 Statement of the Problem

There are many branches of science that are interested in evaporation and evapotranspiration data. But, very less study has been found in Nepalese context. The problem of estimating the water resources and their rational utilization and conservation is important since even now a large part of the land is being somewhat affected by the insufficiency of fresh water. The most reliable method of estimating water resources is the study of water balance and its transformations. Hydrological Water balance is primarily essential. One of the important parameters in calculating the hydrological water balance is Upper evaporative water loss i.e. Evapotranspiration (ET).

There is no doubt that the world is facing two major problems with respect to energy. The first is the continued depletion of fossil fuel reserves and the second is the dramatic increase in global pollution. In the face of these two problems, solar energy would seem to be the most suitable solution, since it is a clean and abundant energy source.

Solar energy is emerging as an alternative energy during the energy crisis. In the 21st century, we are inevitably considering the varied ways of using the Sun‘s energy, of harnessing this bountiful resource for the benefit of mankind. The power from the sun intercepted by the earth is approximately 1.8 x 10^{11} MW which is many thousands of times larger than the present consumption rate on the earth of all commercial energy sources [Oliver, J.E., et. al. (2003)].

The Penman-Monteith (P-M) method is known to be best and widely used method for the estimation of reference evapotranspiration. But it is often discarded because of large amount of weather input parameters that are not frequently available for most of the weather stations. One such parameter is net radiation (R_n) which is the most sensitive parameter for estimating ET using the P-M method and therefore, needs to be accurately estimated (Amatya, 1993; Beven, 1979; Smajstrla and Zazueta, 1994 as cited in Amatya et. al. 2000). When measured R_n is not available, it is often estimated based on sunshine hours and temperature data. There are only very few agro-meteorological and synoptic weather stations in Nepal that measure sunshine hours and dew point temperature that are generally used for estimating solar and net radiation. The data required to compute reference evapotranspiration have not been recorded sufficiently.

Because of the insufficient and unavailability of required data, it has not been given focus to the estimation of evapotranspiration and net radiation in Nepal’s climatic situation. However, ICIMOD and DHM (1996) have published the sunshine hour's maps of Nepal in Climatic and Hydrological Atlas Map of Nepal but not Solar radiation and net radiation maps. In Nepalese context, very less interest has been given to map Evapotranspiration & solar radiation yet so far. Again, large amount of evaporation can be expected under the changing condition of local climate in Kathmandu valley. Thus, thesis research is focused to estimate solar radiation and Evapotranspiration and to map them in GIS environment. Here in this study evapotranspiration is estimated by FAO Penman-Monteith method using climate models for maximum and minimum temperature, Wind speed and Sunshine hours as cited in Pokhrel (1998) and Nayava (2005).

1.3 RESEARCH QUESTIONS

1. How to compute the Radiation and Evapotranspiration rate at a place where climatic and agro-climatic station data are scarce?
2. How to map solar radiations and evapotranspiration over an area?
3. To what extent the study is capable of mapping the Evapotranspiration and radiation?

1.4 SCOPE OF THE STUDY

To feed the ever- increasing population, more water is demanding for the irrigation to produce more food in the developing countries. Nepal's economy is totally based on agriculture. Almost 80% of the total populations are involved in irrigation work and agricultural business. But, only16% of the agricultural lands in the country posses the facility of irrigation. In dry season, due to limited source of water, at some places, farmers do not carry out farming and left the arable farm barren. But in this modern era, irrigation from limited source is possible. Development and planning of irrigation projects, new scientific technology and their implementation are essential for the higher yield of crop. For estimating irrigation water requirement and planning of irrigation system, Evapotranspiration is the principal factor.

Evapotranspiration is given more emphasis in hydrological budgeting, assessing water availability and planning for drought mitigation. The management of increasingly scarce water resources requires information about the evapotranspiration water loss, especially if there are large scale changes in landuse. Evaporation is also a crucial parameter in most crop yield forecasting models. The widely used Food and Agriculture Organization (FAO) crop monitoring and forecasting model is based on evaporation estimates.

Apart from precipitation, the most significant component of the hydrologic budget is evapotranspiration. Evapotranspiration varies regionally and seasonally; during a drought it varies according to weather and wind conditions. Because of these variabilities, water managers who are responsible for planning and adjudicating the distribution of water resources need to have a thorough understanding of the evapotranspiration process and knowledge about the spatial and temporal rates of evapotranspiration.

Solar and net radiation data are frequently used in estimating potential evaporation (PE) from various vegetative surfaces (Amatya et.al., 2000). The methods of estimating solar radiation and new relationships for net radiation may have big implications on estimates of PE. The arrival of considerable quantities of solar energy in the course of one year also creates a prerequisite for its wide utilization for purposes of national economy (Berlyand, 1975). Solar energy could supply all the present and future energy needs of the world on a continuing basis, which makes it one of the most promising of the unconventional energy sources. Solar radiation maps are important for the installation and study of solar power projects.

The amount of solar heat falling on the territory, together with the position, topography and local effects of the area determines the peculiar conditions of formation of the climate of the area and hence it determines the peculiar ecological condition of the area.

So, regarding to the vast implications of Evapotranspiration data on many field and in the absence of radiation and evaporation map in context of Nepal, this thesis work exemplifies the estimation and mapping of the net solar radiation and Evapotranspiration rate at different stations of Kathmandu valley to know its contribution in various fields as mentioned above.

CHAPTER TWO

2. LITERATURE REVIEW

This Chapter is divided into two sections. The first section deals with the theories and concepts regarding Evapotranspiration, Reference Evapotranspiration, its relation with net radiation and its estimating methods. The second section describes the research studies so far undertaken on net radiation estimation and Evapotranspiration computation in general and in context of Nepal.

2.1. THEORIES AND CONCEPTS

2.1.1 Evaporation

According to FAO (1998) - Irrigation and Drainage paper-56, "Evaporation is the process whereby liquid water is converted to water vapor (vaporization) and removed from the evaporating surface (vapor removal)". Water evaporates from a variety of surfaces, such as lakes, rivers, pavements, soils and wet vegetation. Energy is essential to change the state of the molecules of water from liquid to vapor. Direct solar radiation and, to a lesser extent, the ambient temperature of the air provide this energy. The driving force to remove water vapor from the evaporating surface is the difference between the water vapor pressure at the evaporating surface and that of the surrounding atmosphere. As evaporation proceeds, the surrounding air becomes gradually saturated and the process will slow down and might stop if the wet air is not transferred to the atmosphere. The replacement of the saturated air with drier air depends greatly on wind speed. Hence, solar radiation, air temperature, air humidity and wind speed are climatological parameters to consider when assessing the evaporation process.

Where the evaporating surface is the soil surface, the degree of shading of the crop canopy and the amount of water available at the evaporating surface are other factors that affect the evaporation process. Where the soil is able to supply water fast enough to satisfy the evaporation demand, the evaporation from the soil is determined only by the meteorological conditions. However, where the interval between rains and irrigation becomes large and the ability of the soil to conduct moisture to pear the surface is small, the limited availability of water exerts a controlling influence on soil evaporation.

2.1.2 Transpiration

According to FAO (1998) - Irrigation and Drainage paper-56, Transpiration consists of the vaporization of liquid water contained in plant tissues and the vapor removal to the atmosphere. The vaporization occurs within the leaf, namely in the intercellular spaces, and the vapor exchange with the atmosphere is controlled by the stomatal aperture. Nearly all water taken up is lost by transpiration and only a tiny fraction is used within the plant.

Transpiration, like direct evaporation, depends on the energy supply, vapor pressure gradient and wind. Hence, radiation, air temperature, air humidity and wind terms should be considered when assessing transpiration. The soil water content and the ability of the soil to conduct water to the roots also determine the transpiration rate. The transpiration rate is also influenced by crop characteristics, environmental aspects and cultivation practices. Different kinds of plants may have different transpiration rates. Not only the type of crop, but also the crop development, environment and management influence the transpiration rate.

2.1.3 Evapotranspiration (ET)

According to FAO Irrigation and Drainage Paper-56, Evaporation and transpiration occur simultaneously and there is no easy way of distinguishing between the two processes. Evapotranspiration is the sum of the water used by plants in a given area in transpiration and the water evaporated from the adjacent soil in any specified time.

2.1.4 Units

The evapotranspiration rate is normally expressed in millimeters (mm) per unit time. The rate expresses the amount of water lost from a cropped surface in units of water depth. The time unit can be an hour, day, decade, month or even an entire growing period or year. As one hectare has a surface of 10000 m^2 and 1 mm is equal to 0.001 m, a loss of 1 mm of water corresponds to a loss of 10 m^3 of water per hectare.

Water depths can also be expressed in terms of energy received per unit area. The energy refers to the energy or heat required to vaporize free water. This energy, known as the latent heat of vaporization (l), is a function of the water temperature, which is about 2.45 MJ kg^{-1} at 20°C. In other words, 2.45 MJ are needed to vaporize 1 kg or 0.001 m^3 of water. Therefore, 1 mm of water is equivalent to 2.45 MJ m^{-2}. The evapotranspiration rate expressed in units of MJ m^{-2} day^{-1} is represented by l ET, the latent heat flux.

	Depth	**volume per unit area**	**energy per unit area ***
	mm day^{-1}	m^3 ha^{-1} day^{-1}	MJ m^{-2} day^{-1}
1 mm day^{-1}	1	10	2.45
1 m^3 ha^{-1} day^{-1}	0.1	1	0.245
1 MJ m^{-2} day^{-1}	0.408	4.082	1

* For water with a density of 1000 kg m^{-3} and at 20°C

(Source: FAO (1998) - Irrigation and Drainage paper-56)

2.1.5 Factors Affecting Evapotranspiration (ET)

The rate of ET for a given environment (vegetation) is a function of four critical factors. The first and most critical factor is soil moisture. Evaporation can not take place if there is no water in the soil. However, if adequate soil moisture is available, three additional factors — plant type, stage of plant development and weather — affect ET rate.

Plant type refers to the species or variety of plant being grown and can greatly influence the rate of ET. Grass and many non-native plants require considerable water when grown in the desert. In contrast, many native plants are adapted to the desert and require much less water. Stage of plant development also plays a critical role in determining ET. Plant development encompasses both the relative activity of the plant (e.g. dormant vs. actively growing) and plant size.

Weather is the fourth and last of the critical factors affecting ET. Weather conditions dictate the amount of energy available for evaporation and therefore play a crucial role in determining ET rate. Four weather parameters — solar radiation (amount of sunshine), wind speed, humidity and temperature — impact the rate of ET.

Solar radiation contributes huge amounts of energy to vegetation in the desert and thus is the meteorological parameter with the greatest impact on ET on most days. In actuality, solar radiation is one component of the total radiant energy balance of vegetation referred to as net radiation. Invisible, infrared radiation represents the other component of net radiation. On most days, however, solar radiation is the dominant component of net radiation because the infrared balance is negative and often small.

Wind is the second most important factor in determining ET rate. The wind has two major roles; first, it transports heat that builds up on adjacent surfaces such as dry desert or asphalt to vegetation which accelerates evaporation (a process referred to as advection). Wind also serves to accelerate evaporation by enhancing turbulent transfer of water vapor from moist vegetation to the dry atmosphere. In this case, the wind is constantly replacing the moist air located within and just above the plant canopy with dry air from above.

Humidity and temperature work in concert with each other to determine the dryness or drying power of the atmosphere. The vapor pressure deficit (VPD) is the meteorological variable used to quantify the drying power of the atmosphere. The VPD estimates the difference (or gradient) in vapor pressure (concentration of water vapor) between the moist vegetation and the drier atmosphere above. Relative humidity, the humidity variable most commonly reported in weather forecasts, is a poor indicator atmospheric dryness.

Excess of the relative atmospheric humidity ceases evapotranspiration. The airflow circulation may blow away the water vapour from evaporation surface on which saturation air is distributed by wind.

The final parameter affecting ET rate is temperature. Temperature impacts ET through its impact on VPD and advection. In addition to these factors temperature impacts ET is some more subtle ways. When all other factors are equal, ET will be higher for warm as compared to cool vegetation because less energy is required to evaporate water from the warm vegetation. Temperature also impacts the relative effectiveness of the radiant energy and wind in evaporating water. Radiant energy is more effectively utilized for ET when temperatures are high. In contrast, wind has more impact on ET when temperatures are low.

2.1.6 Evapotranspiration and Solar Radiation Components

Evaporation of water requires relatively large amounts of energy, either in the form of sensible heat or radiant energy. Therefore the evapotranspiration process is governed by energy exchange at the vegetation surface and is limited by the amount of energy available. Because of this limitation, it is possible to predict the evapotranspiration rate by applying the principle of energy conservation. The energy arriving at the surface must equal the energy leaving the surface for the same time period.

When components of the solar spectrum reach the earth, they are partially absorbed and converted to thermal energy. Only a small part of insolation is absorbed directly in the atmosphere, where it is transformed into heat and chemical energy. Radiation, convection, and conduction bring about heating and cooling of air by transferring energy between the earth‘s surface and the air and between different levels in the atmosphere. In addition, evaporation and condensation of water affect exchanges of latent heat between various surfaces and the overlying air. Eventually the energy returns to outer space as long wave terrestrial radiation, maintaining the earth's radiation balance.

The net radiation (R_n) is the difference between all incoming and out going radiation. R_n can be calculated from solar radiation or sunshine hours, temperature and humidity data [FAO, 1998]. The amount of radiation received at the top of the atmosphere (R_a) is dependent on latitudes and time of year only. Part of R_a absorbed and scattered when passing through the atmosphere. The remainder, including some that is scattered but reaches the earth surface, is identified as incoming solar radiation (R_s). R_s is dependent on R_a and the transmission through the atmosphere, which is largely, depends on cloud cover. Part of R_s is reflected back directly by the soil and crop and is lost to the atmosphere. Reflection (α) depends on the nature of the surface cover and is approximately 5-7% for water and around 15 to 25% for most crops. This factor varies with degree of crop cover and wetness of the exposed soil surface. That which remains is net shortwave radiation (R_{ns}).

All incoming heat is considered to be released by the ground surface by ignoring heat storage and the energy advected by evaporation. The release consists of atmospheric heating (composed of short-wave reflection, net long wave exchange, sensible heat exchange, net atmospheric advection, and net hydrospheric advection), evapotranspiration. Thus, the total heat available for evapotranspiration over a day is composed of the heat actually used for evapotranspiration and that used for atmospheric heating. The several processes that deplete the incoming solar radiation as it passes into the atmosphere include reflection, scattering, absorption and transmission.

Additional loss at the earth's surface occurs since the earth radiates part of its absorbed energy back through the atmosphere as long wave radiation. This is normally greater than the down coming long wave atmospheric radiation. The difference between outgoing and incoming long wave radiation is called net long wave radiation (R_{nl})

Total net radiation (R_n) is equal to the difference between $R_{ns} – R_{nl}$.

2.1.7 Reference Evapotranspiration and FAO Penman-Monteith Equation

ETo refers to the water removed from a unit ground area completely covered with a reference crop, healthy and unstressed and with ample water supply (Allen et al., 1998; Walter et al., 2000). In the real world, ETo is computed from a mathematical formula such as the Penman or Penman-Monteith Equation. The FAO penman-Monteith method calculates reference evaporation ETo or Potential evapotranspiration on the basis of the following-

- The aerodynamic and surface characteristics of a reference surface, that is, a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 sm^{-1} and an albedo of 0.23 (FAO 1998). This reference crop closely resembles an extensive surface of green grass of uniform height, actively growing, completely shading the ground and with adequate water.
- The FAO Penman-Monteith equation (FAO, 1998) requires location parameters of the station such as elevation above sea level, and latitude. It also needs input data of radiation, air temperature, wind speed and humidity on a daily basis for daily calculations.

The ETo computation is always made for the same reference surface — a tall, well-watered, cool season grass. Therefore, three of the four factors that can affect ET namely, crop type, stage of crop development and soil moisture do not change and can not affect the ETo calculation. Only the fourth factor — weather — is allowed to vary in the ETo calculation. Misssing climatic data are estimated from climate models or on the basis of estimation approaches from FAO (1998) where possible. Three of the four weather parameters used in the ETo computation — solar radiation, temperature and vapor pressure deficit (VPD) — have distinct annual cycles. Wind speed, by contrast, varies considerably but follows a much less distinct annual cycle. The cyclic nature of solar radiation, temperature, and VPD produce a distinct annual ETo cycle.

2.2. REVIEWS ON STUDIES OF EVAPOTRANSPIRATION AND ITS ESTIMATION

2.2.1 International Review

2.1.1.1 Review of studies on Evapotranspiration and its Estimation

The daily weather plays a significant role in evapotranspiration. Owing to the difficulty of obtaining accurate field measurements, ET is commonly computed from weather data. It is not always possible to perform experiments in soil water for crop water but suitable climatic model also helps to determine crop water requirement. The influence of climatic factors such as temperature, humidity, wind, vapour pressure and solar radiation etc. on evapotranspiration has been studied by various researchers. A number of equations have been utilized to estimate evapotranspiration such as Thronthwaite (1948), Hamon (1961), Penman (1948), Priestely and Taylor (1972), Morton (1978), etc. Blaney and Criddle had used temperature in the arid Western US as principal variable to get an index to the consumptive use of plants i.e. Evapotranspiration. Temperature and solar radiation were used by Jensen and Haise to estimate the consumptive use of alfalfa. Hargreves estimated the ET for grass as the reference crop [cited in Shrestha, A. 1998].

To calculate the monthly evapotranspiration estimate using Thronthwaite or Hamon equations is easy because these equations require only air temperature as input data. The effects of vegetation on evapotranspiration could not be incorporated by these methods, and the value calculated by the Thronthwaite equation was higher in summer and lower in winter than the observed data in Japan [Nakagawa (1984) reported in Shrestha, A (1998)].

Penman (1948) in England had made the most complete analysis using several climatic variables. Penman linked the evapotranspiration rate to the available energy on the surface and the effective drying of the surface by moving air. The original Penman equation (1948) predicted evaporation losses from an open water surface, and then it was related to grass evapotranspiration by experimentally determined crop coefficients ranging from 0.6 in winter months to 0.8 in summer months for the climate of England. The Penman equation consists of two terms; the radiation term and aerodynamic term. Under calm weather conditions, the original Penman equation using a crop coefficient of 0.8 has been found to predict evapotranspiration closely, not only in cool humid regions as in England, but also in very hot and semi-arid regions.

Monteith (1965) introduced stomata's resistance and aerodynamic resistance into the Penman equation. Penman-Monteith method for the estimation of reference evapotranspiration utilized the best features of energy-balance and mass transfer approaches.

Priestly and Taylor (1972) simplified the Penman equation by redefining potential evapotranspiration. The potential evapotranspiration was defined as the evapotranspiration from a horizontally uniform water-saturated surface with minimal advection. Evapotranspiration data obtained over several open water and saturated land surfaces were analyzed and overall mean ratio was calculated. However, the values of the ratio had been found to vary widely even under wet soil conditions.

Doorenbos and Pruitt (1977) modified Penman equation using a revised wind function. The modified Penman equation had taken into consideration of net radiation, wind turbulence and the aridity of the air as evaporative forces. The modified Penman equation has been used extensively worldwide. However, the method, to some extent, overpredicts ETo under known advective conditions. Considerable deviation for high wind values has been observed. Inconsistencies were observed in the standardization of wind function and in the adjustment factor.

Morton (1978) described the areal evapotranspiration model [cited in Shrestha, 1998]. The model was based on the complementary relationship between the evapotranspiration from an area and the potential evapotranspiration at a certain point in the area, calculated using the modified Penman and Priestly-Taylor equations. Once the point potential ET and areal potential ET are estimated, the complementary relationship can be used to give an estimate of the areal actual ET. It was found that Morton's estimates of mean annual areal actual ET gave good spatial trend but were not accurate in absolute values. Consequently, adjustments to Morton's estimates were made to remove bias and extremes.

Several semi-empirical and empirical relationships for evaporation have been developed, but they were very site specific (e.g., non-transferable). The Penman-Monteith method (Monteith, 1981), which combines energy balance and mass transfer methods, has been used extensively in both arid and humid climates to provide estimates of ETo. This method depends on many variables that are usually hard to measure or estimate accurately. Actual evapotranspiration is calculated by spatial interpolation of ETo between the sites, and by the application of landscape specific crop coefficients which are a function of water depth.

Jensen et al. (1990) had stated that more reliable solar radiation estimates are obtained by recorded percent sunshine data as compared to cloud cover data as the later is more qualitative.

Wallace et. al. (1993) had highlighted the importance of knowing not only total evaporation but also how the total is partitioned between its components transpiration and soil evaporation since only transpiration is related to yield.

The Penman-Monteith equation has important significance in the understanding of the water transfer process through the soil-plant atmosphere system. As a result of an Expert Consultation held in May 1990, the FAO Penman-Monteith method is now recommended as the standard method for the definition and computation of the reference evapotranspiration, ETo [FAO, 1998].

FAO (1998) reported that "Reference evapotranspiration" or ETo is the amount of water needed by grass and ETo is one of the most important meteorological parameter to consider when scheduling run times for irrigation system. Crop water evapotranspiration under standard condition (ETc) is the evapotranspiration from the disease free, well-fertilized crop, grown in the large fields under optimum soil water condition and achieving full production under the given climatic condition. The weather components of solar radiation, relative humidity, wind run, and air temperature are used to estimate a reference crop ETo. When combined with a crop coefficient, the reference crop ETo can be used to estimate actual crop ET. The FAO-56 Penman-Monteith equation has been recommended by FAO to present the definitions and methods of estimation of the reference grass (albedo = 0.23, height = 0.12 m, surface resistance = 70 s/m) evapotranspiration.

Amatya et al. (1995) used the published relationships with measured solar radiation to estimate the net radiation and vice versa for evaluating five different methods of estimating ETo in eastern North Carolina. [cited in Amatya et. al., 2000]

Allen, R.G (1999, 2000, 2002), the 'ETo program (Reference Evapotranspiration Software)' provided standardized calculations of reference evapotranspiration for fifteen of the more common methods and equations that were in use in the United States and Europe. The calculations are based on the weather data measurements that are made available by the user. ETo program (software) provided calculations that were compatible with United Nations Food and Agriculture Organization (FAO) Irrigation Paper No. 56 (Allen et al., 1998) and with standardized forms of the ASCE Penman-Monteith equation recommended in 2000 by the ASCE Task Committee on Standardized Evapotranspiration Calculations. Reference ET methods calculated by ETo program (software) for Windows version 2 include the ASCE and FAO Penman-Monteith equations, Kimberly Penman, CIMIS Penman, FAO-24 Penman, FAO-PPP17 Penman and 1948 Penman equations, FAO-24 Radiation, Blaney-Criddle and Pan evaporation equations, and Priestley-Taylor, Turc, Makkink and Hargreaves equations. Both clipped grass and alfalfa references can be computed. [http://www.kimberly.uidaho.edu/ref-et/body.html]

Simple calculations of PET can be based on sun, wind, temperature, and humidity. The estimates are usually first derived for a single situation, such as grass, and then adapted for other plants because water use varies widely from plant to plant. *Tree Fruit Irrigation*, edited by K. Williams & T. Ley had provided "Penman calculator (PET Calc) for water use by grass" web page [http://www.tfrec.wsu.edu/Orchard/pET/README.html].

Amatya et.al., (2000) studied Solar and Net Radiation for estimating Potential Evaporation from three Vegetation Canopies. Weather parameters such as air temperature, relative humidity, wind speed, solar radiation, and net radiation have been continuously monitored using automated sensors to estimate PE for three different vegetation canopies in the coastal plain of North Carolina. Mean daily solar radiation, among these three stations varied within about 70 % only. Mean daily net radiation on pine forest canopy was at least 24% higher than on grass vegetation at the same latitude, indicating that use of net radiation from a forest site in Penman based methods may well overestimate the PE for grass vegetation. Compared to daily values the monthly estimates were in better agreement with measured data.

Samani, Z. (2000) introduced a procedure to estimate solar radiation and subsequently reference crop evapotranspiration using minimum climatological data. The paper described a modification to an original equation that uses maximum and minimum temperature to estimate solar radiation and reference crop evapotranspiration. The proposed modification allowed for the correction of errors associated with indirect climatological parameters affecting the local temperature range. The proposed modification also improves the accuracy of estimates of solar radiation from temperature.

Department of Geography, University of Oregon (2000) published Global Climate Animations that depicted all the 12 month's global energy balance, Air temperature, Global water balance, and atmospheric circulation and winds. The Global Climate Animations can be downloaded as animated .gif or Flash .swf formats [http://geography.uoregon.edu/envchange/clim_animations.htm].

Wang, Q.J., et. al, (2001) provided derived data on both ET and actual ET. Three variables areal actual ET, areal potential ET and point potential ET were mapped. For each variable, there was one mean annual map and twelve mean monthly maps. Morton's (1983) complementary relationship areal ET model was used to derive the estimates of areal potential ET, point potential ET and areal actual ET. The mean monthly actual ET values were proportionately adjusted according to the adjustments made to the mean annual actual ET values. The adjusted areal actual ET estimates were interpolated to give gridded values. The gridded annual areal actual ET values were compared with the latest available rainfall maps (Bureau of Meteorology, 2000), and adjusted to ensure that the annual areal actual ET did not exceed rainfall and that the runoff coefficients were reasonable.

Vamsee, M. V. (2005) evaluated the relative influence of potential evapotranspiration to solar radiation on vegetation patterns in the West Potrillo Mountains, New Mexico.

Donatelli et. al. (2005) provided Evapotranspiration (ET) - a cross-platform software component containing routines to estimate daily and hourly values of reference evapotranspiration (and related variables) according to alternative approaches.

Kizer, M. developed "the Oklahoma Evapotranspiration Model", a weather-based tool for the estimation of daily water loss from a plant canopy through the combined processes of evaporation and transpiration. Using weather data from the Oklahoma Mesonet, the model calculates daily grass reference evapotranspiration (EToG) for each Mesonet site, and, based on those values, estimates daily values for alfalfa reference ET, cool-season grass ET (e.g., a fescue lawn), warm-season grass ET (e.g., a bermudagrass lawn), and pan evaporation. The model uses the FAO-recommended Penman-Monteith equation and the computational procedures found in Allen et al. (1994a, 1994b).

The mean potential evapotranspiration in the Hind-Kush Himalaya region ranges from about 1000 mm in the high areas of the Tibetian plateau to about 2000 mm in the Tharr Desert. In general, a decreasing gradient from south to north and from east to west can be seen. [Shrestha,1998]

As cited in U.S. National Report to IUGG, 1991-1994 Rev. Geophys. Vol. 33 Suppl., remote sensing does have two potentially very important roles in estimating evapotranspiration. First, remotely sensed measurements offer methods for extending point measurements or empirical relationships, such as the Thornthwaite [1948], Penman [1948] and Jensen-Haise [1963] methods, to much larger areas, including those areas where measured meteorological data may be sparse. Secondly, remotely sensed measurements may be used to measure variables in the energy and moisture balance models of ET.

2.2.1.2 Studies on Solar radiation and its measurement

T. G. Berlyand (1970) investigated the regime of solar radiation in Africa on the basis of observational data obtained from the Actinometric network. The distribution of total radiation over the territory and peculiarities of its annual amplitude were analyzed. In, addition to the data from the actinometric network, the data obtained by an indirect method were also included in the paper for determination of the ratio of scattered to total radiation. Maps of absolute and relative day to day variations of total radiation were complied. The comparative stability of diurnal values of Total radiation over a large part of the continent was shown.

Paltridge and Proctor (1975) theoretically computed data on the monthly average values of solar radiation at the forty three sites over the Australian continent based on available data. Tables of monthly mean solar radiation parameters were computed from detailed cloud cover information. The parameters included direct and global daily total energy inputs to horizontal, inclined and "sun-tracking" surfaces. Comparison with measured global radiation at 12 stations revealed virtually no systematic error in the computation scheme, and an error of 2 MJ m^{-2} day^{-1} in the worst case month of any station.

The information about the solar energy available and climatic conditions at a site can be obtained only from direct measurements collected at the site. Phenomenological modeling can be done and in general and specific features of the models can be identified and separated by comparison with the models for other sites. Goldberg and Klein (1977) initiated the modeling for three widely separated locations, Barrow, Alaska (71^0 N); Rockville, Maryland (39^0 N) and Balboa, Canal Zone in Panama (9^0 N). The thesis concluded that long term continuous measurements at a variety of locations are needed before any realistic solar energy models.

Georgia et. al. (2002) carried out the comparative study of solar radiation in urban and rural areas by considering two cities Sao Paulo which represented an urban area and Botucatu which represented a rural area in Brazil. In these two cities the measurements of global and diffuse solar radiation were carried out from 1996 to 2001 using set of pyranometers. The seasonal evolution of monthly averaged values of daily and hourly global and diffuse solar radiation at the surface were estimated based on observations carried out in the two cities. The frequency distributions of clear days indicated that in Botucatu occurred a larger number with clear sky days than in Sao Paulo. During 1996 – 2001 it was observed that clear sky days were about 4.0% of time in Sao Paulo and about 99.9% in Botucatu.

Pinde Fu and Paul M. Rich had developed "The Solar Analyst" as an ArcView GIS extension using C++, Avenue, and the GridIO library. The Solar Analyst was a geometric solar radiation modeling tool, calculated insolation maps using digital elevation models (DEMs) for input.

Highly optimized algorithms account for the influences of the viewshed, surface orientation, elevation, and atmospheric conditions. The Solar Analyst provides a convenient and effective tool for understanding spatial and temporal variation of insolation at landscape and local scales [Retrieved in 2005 from http://gis.esri.com/library/userconf/proc99/proceed/papers/pap867/p867.htm]

2.2.2 Review from Nepal

Nayava (1981) has developed multiple regression equations to estimate mean maximum temperature and monthly minimum temperature considering thirty five climatological stations in Nepal. Similar studies for extrapolating temperature data were done by Kenting Earth Science Ltd (1982) [cited on Nayava (2005)].

Lambert and Chitrakar (1989) has showed a decreasing trend for potential evapotranspiration with increasing elevation in Nepal. Evapotranspiration Studies of Lambert and Chitrakar (1989), MacDonald & Partners (1990), MacDonald (1990) used the method as proposed by FAO (1977), which, according to FAO (1998) was reportedly found to frequently overestimate ETo.

Chhetri (1993) studied the evaporation distribution over Nepal. Evaporation data obtained from twenty Agro-meteorological stations scattered throughout the various parts of the country had been used to study the evaporation distribution over Nepal. The distribution of evaporation rate in country at various seasons of the year had been shown by drawing isolines. Latitudinal, longitudinal, Altitudinal distribution of evaporation had been studied and an empirical equation had been developed to estimate evaporation at specified altitude.

Shakya (1995) had estimated PET (Potential Evapotranspiration) for station Daman by using Thronthwaite method in relation to the study of the meteorological and hydrological condition.

ICIMOD and DHM (1996) have used the multiple regression method to estimate the various mean monthly climatological parameters and used those data in preparing “Climatic and Hydrological Atlas Map of Nepal”.

Dhakal, M. (1996) as cited in Shrestha (2004) had attempted water balance in Nepal by imposing evapotranspiration estimated from Thronwaite method in his unpublished M.Sc. dissertation.

Shrestha, Archana (1998) has attempted to estimate evapotranspiration in Kulekhani Area from field measurement.

Shrestha, Hasana (1998) [cited in Shrestha (2004)] had determined the crop water requirement by using climatic approach. Calculation of reference crop evapotranspiration from direct method using Penman Monteith equation was experimented. She had concluded that the estimated and measured crop reference evapotranspiration are very close to each other with highest evapotranspiration rate in the month of July because of high temperature and less relative humidity. But the experiment was conducted with limited meteorological data.

Adhikary S. and Shakya B. (2000) observed albedos of dusted ice surfaces & bare ice regarding to the net radiation and reported that albedo of the ice surfaces covered with dust decreased with increasing concentration of dust.

Juerg Merz (2004), ICIMOD publication had calculated Potential evapotranspiration using a temperature-based method on the basis of the data available for the Jhikhu and Yarsha Khola catchments. In this context the FAO Penman-Monteith method with limited climatic data as proposed by FAO (1998) was selected. In this study, the temperature, wind, radiation and humidity parameters for the Jhikhu Khola and Yarsha Khola catchments were discussed and the results of the potential evapotranspiration calculations were presented and discussed on the basis of temporal and spatial distribution. Finally, Actual evapotranspiration is determined for the calculation of water balances. The missing climatic data were estimated from short-term measurements in the catchment, from data of stations close or on the basis of estimation approaches from FAO (1998). The estimated parameters are validated on the basis of measured data sets on the two catchments, from the Godavari Training & Demonstration site of ICIMOD, or on the basis of literature.

Chhetri (2000) estimated the evapotranspiration rate on land surface at Kyangjin in Langtang valley in order to know the contribution of evaporation for energy and water balance studies. The average daily evaporation rate calculated from latent heat loss was 4.2 mm d^{-1} at Kyangjin.

Shilpakar (2003) assessed the evapotranspiration using the Surface Energy Balance Algorithm for Land (SEBAL) complemented by a mountain radiation model for water accounting applying remote sensing in East Rapti river basin. According to him, Droogers and Allen (2002) had reported that Hargreaves (1985) method is very much simpler and less data demanding than the Penman-Monteith equation. But major drawback of this method is that it overestimate ETo in humid area. They had revised the Hargreaves (1985) equation using global Water and Climate Atlas published by IWMI. But, the Original Hargreaves (1985) and Modified Hargreaves (2002) equations for estimating ETo, both overestimate the ET.

Nayava (2005) estimated the evapotranspiration by climate models for western Nepal. He stated that among the empirical formulae to compute evapotranspiration, Penman and Monteith method is the best in Nepalese conditions. Various models were developed to expand the required climatic parameters to estimated evapotranspiration, for all the rainfall points where data not available. Multiple Regression equations were used to extend climatic parameters and evapotranspiration rates were estimated by the 'CROPWAT' software developed by FAO (1998).

Shakya, B. and Shrestha, S. (2004) have performed experiments from april to July 2004 to determine the grass evapotranspiration (ETo) in the T. U. micro-catchment. Penman-Monteith model was used to check the results on ETo. The estimated and measured reference crop evapotranspiration were found to be close to each other. The estimated ETo were 4.0 mm/day in June and 3.22 mm/day in July.

Lohani (2005) in her unpublished M.Sc. dissertation computed crop water requirement experimentally and by using Penman-Monteith method. She concludes that to estimate crop water requirement from limited data Penman-Monteith method appeared to be the most reliable method. As the installation of automatic synoptic station is costly and Penman-Monteith method needs sophisticated meteorological data, experimental method is a very attractive alternative. However, for simplicity, pan evaporation method may help to determine rough actual Evapotranspiration.

CHAPTER THREE

3. THESIS OBJECTIVE

3.1 RESEARCH GAPS

Several gaps in monitoring or estimation of input parameters and selection of appropriate method of solar radiation and evapotranspiration rates have been identified from Literature review. Unavailability of required input climatic data and lack of valid model for the estimation are the key issues.

Few researches on solar radiation and Evapotranspiration have been found in the context of Nepal. There are controversies among the different scientist groups regarding Evapotranspiration estimation. Nayava (2005) stated that among the empirical formulae to compute evapotranspiration, modified Penman-Monteith method is the best in Nepalese conditions but there are several forms of Penman-Monteith Equations in existence for ETo estimation. Unfortunately, each modified Penman Equation (and Penman-Monteith procedure) differs slightly and will, if supplied with the same weather data, produce a different ETo values. Hence, a standard and valid procedure is necessary.

Again all required hydro-meteorological parameters like temperature, net solar radiation are not feasible to measure in all the climatological stations. Various models have been developed to expand the climatic parameters for all the rainfall points. The expansion and extrapolation of available data over the latitude, longitude and altitude are necessary and their validity should be tested.

Solar radiation is an important weather variable for several agro-environmental studies. The number of ground-level weather stations recording daily radiation is very small compared to the number recording air temperature and precipitation. Radiation can be computed meteorologically using different parameters such as cloud cover, temperature, etc. But very few studies have been found in this context and hence require standard valid equations for computation.

So far, in Nepal, radiation and evapotranspiration maps have not been prepared by any agencies, but, at least, sunshine hour map is available for Nepal [ICIMOD 1997]. The ideas regarding the patterns of solar radiation distribution could be obtained from the climatic atlas constructed and published by ICIMOD on the basis of total Sunshine hour’s data.

3.2 Thesis Objective in Detail

Maps of evapotranspiration and the radiation have not been found in climatic atlas of Nepal. In Kathmandu valley radiation and evapotranspiration map would be best tool for environmental and agricultural studies, thus the thesis research is mainly focused on estimation and mapping of Solar radiation and Evapotranspiration. The specific objectives of thesis are as follows.

Specific objectives

- To estimate solar radiation and net radiation following the guidelines and empirical relationships
- To estimate Reference Evapotranspiration rate i.e. ETo over Kathmandu valley using FAO Penman-Monteith equation reported by Allen et. al (1998) and
- Preparation of solar radiation and evapotranspiration maps of Kathmandu Valley

The data and methods tested here will present a basis for evaluation of reliability of estimation of temperature, wind speed and sunshine or radiation data in estimating ETo in Nepal.

3.3 Limitation of Study

The study is limited to the watershed boundary of Kathmandu valley covering catchment area of 583 km^2. Among the meteorological stations in and around Kathmandu valley, seventeen stations are considered for the study. Estimation of input climatic parameters of Kathmandu valley has been carried out for temperature, Rainfall, Humidity, Sunshine hours and Wind speed. Research is specially focused on estimation of reference evapotranspiration in Kathmandu valley. The set of input parameters have been estimated using the climatic models cited in Pokhrel (1998) and Nayava (2005). The Reference Evapotranspiration has been estimated using FAO Penman-Monteith equation (Allen et. al. 1998) & Radiation components (R_s and R_n) have also been derived as an auxiliary parameter using methods cited in Allen et.al. (1998) & Shakya (2004).

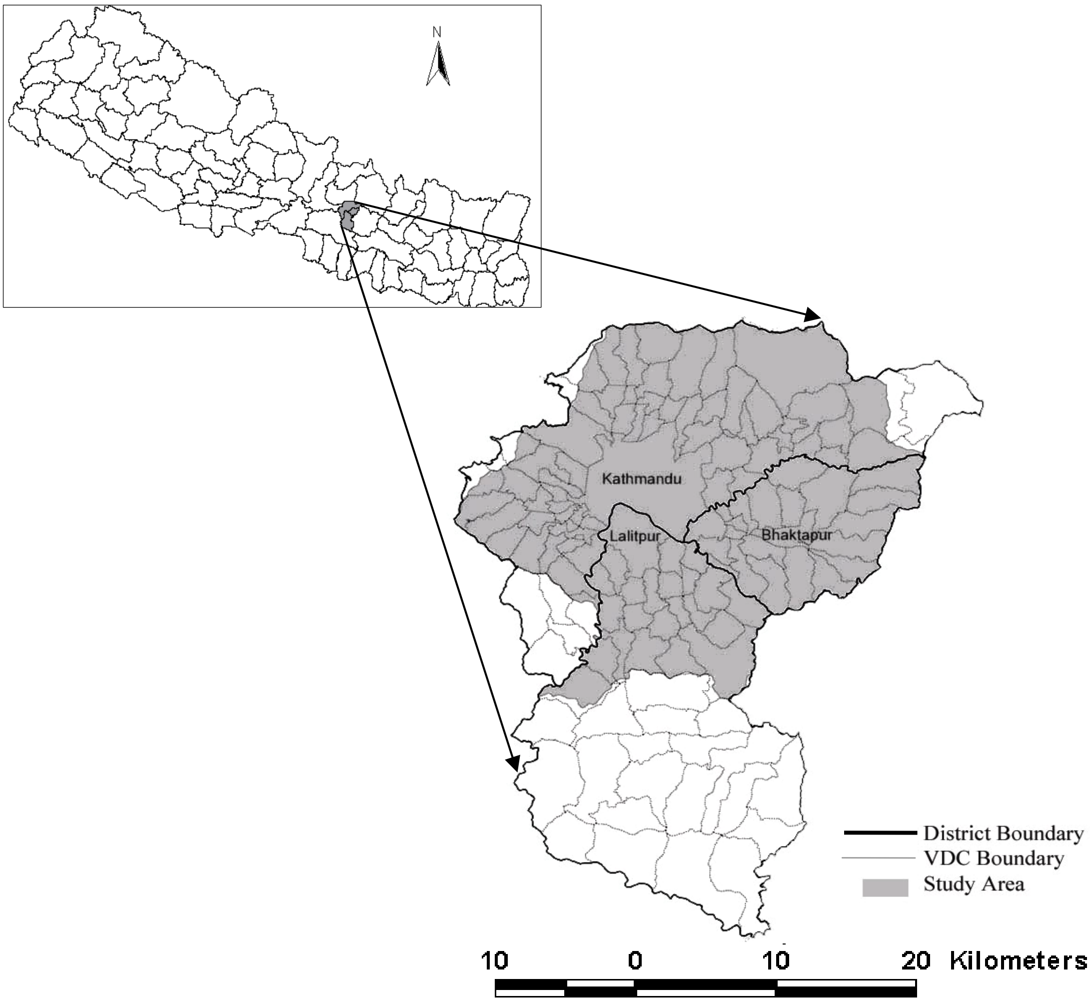
For mapping purpose, the required digital maps like, Kathmandu valley boundary maps, landuse have been collected from ICIMOD and software like ArcView GIS and Ms-Excel worksheets have been used. The mapping of ET estimates is affected by the spatial coverage of the climate stations available, and by the interpolation techniques used. Here, point value interpolation for whole valley has been carried out.

The measured values of all input climatic parameters are missing, so the availability of data limits the study and as the study uses the empirical models, error may arise in the estimated data. The ET estimate and maps presented here are subject to error from a number of sources. The basic input data used may be subjected to measurement error. In addition, there is also the model error in deriving the ET estimates. These maps are just a graphical visualization of spatial pattern of computed parameters. This is an academic work for the partial fulfillment of requirements for the degree of Master of Science in Environmental Science. Therefore, available time and financial resources limit the scope of the work. It is clear that available data for research purpose is very much limited.

CHAPTER FOUR

4. THE STUDY AREA

This chapter highlights different settings, comprising physical, land use, economic and social status of the study area – Kathmandu valley.



(Source: ICIMOD, 2000)

Figure 1 : Location of Kathmandu, Lalitpur and Bhaktapur districts and Kathmandu Valley based on the Watershed boundaries

4.1 LOCATION AND TOPOGRAPHY

Kathmandu Valley lies in the central hill region of Nepal. The valley with bowl shape is 19 by 30 kilometers. The valley region comprises three districts, viz. Bhaktapur, Kathmandu and Lalitpur. There are altogether 130 village development committees (VDCs) in the Kathmandu district, Lalitpur district, and Bhaktapur district: 67 in Kathmandu, 41 in Lalitpur, and 22 in Bhaktapur. But over study area there are 99 VDCs.

The area of Kathmandu Valley is based on a watershed boundary covering 81 per cent of Kathmandu district, 32 per cent of Lalitpur district, and the whole of Bhaktapur district (Figure

1). The reported area ranges from 596 to 760 sq. km. (IUCN and HMG/N 1995). In this study, the area of the Kathmandu Valley is calculated from a topographic map on a scale of 1:25,000; the area is 583 km^2 (ICIMOD 2000).

Shivapuri lekh (mountain 2689 m) in the north, Phulchoki ridge in the south and Sanga Bhanjyang (pass) in the east are the valley‘s prominent boundary features. The perimeter of the valley is defined by the ridgeline which forms the limits of its watershed. The floor of the valley lies at an average elevation of 1250m from the mean sea level from which mountains rise rather steeply on all sides above 1800m the highest being the Phulchoki ridge with elevation of 2831 m in the south-east (Pradhan 1998). The lower and gentler slopes have been used for terrace cultivation and forests are found only on higher elevations.

4.2 METEOROLOGICAL STATIONS

Sixteen meteorological stations have been considered for the study. The meteorological stations are listed in Table 1.

Table 1 : Meteorological stations considered for study

Station Index	Station Name	Latitude	Longitude	Elevation in m
1007	Kakani	27 48 00	85 15 00	2064
1015	Thankot	27 41 00	85 12 00	1630
1021	Kirtipur (Bagbani)	27 41 00	85 18 00	1364
1022	Godawari	27 35 00	85 23 10	1400
1029	Khumaltar	27 40 00	85 20 00	1350
1030	Kathmandu airport	27 42 00	85 21 50	1336
1035	Sankhu	27 44 00	85 29 00	1449
1039	Panipokha	27 44 00	85 21 00	1335
1043	Nagarkot	27 42 00	85 31 00	2163
1052	Bhaktapur	27 40 00	85 25 00	1330
1059	Changu narayan	27 43 00	85 25 00	1543
1060	Chapa gaun	27 36 00	85 20 00	1448
1061	Lubhu	27 38 30	85 23 00	1341
1071	Buddhanilkantha	27 47 00	85 21 40	1350
1073	Khokana	27 38 00	85 17 00	1212
1074	Sundarijal	27 46 00	85 25 20	1490
1075	Lele	27 35 00	85 17 00	1590

(Source: DHM)

4.3 CLIMATE

The Kathmandu valley region lies in the sub-tropical to temperate climate zone. There is great variation in temperature condition between the valley basin and the surrounding hill ridge. According to FAO/WMO climatic classification [Shakya, 2004], the climate of valley floor lies at moist sub humid to humid climate, whereas, around hilly areas the humid climate persists. According to Department of Hydrology and Meteorology (DHM), mean annual precipitation at the study area ranges between 1500mm to 2000mm. At Nagarkot and Thankot hills, annual rainfall exceeds 1500 mm, whereas in Kathmandu Valley, annual rain falls below 1500 to around 1500mm. The south-east monsoon is the main rain bearing wind which delivers about three fourths of the total rainfall during the wet summer seasons from June thorough September. While the winter months remain mostly dry, occasional precipitation occurs in the form of winter rains caused by westerly cyclones. Geographically, rainfall in the valley is not evenly distributed. The highest precipitation is on the southern slopes of Shivapuri lekh. The amount declines considerably from the surrounding ridge to the valley. The spatial pattern of annual rainfall in the Kathmandu valley is presented as figure 2.

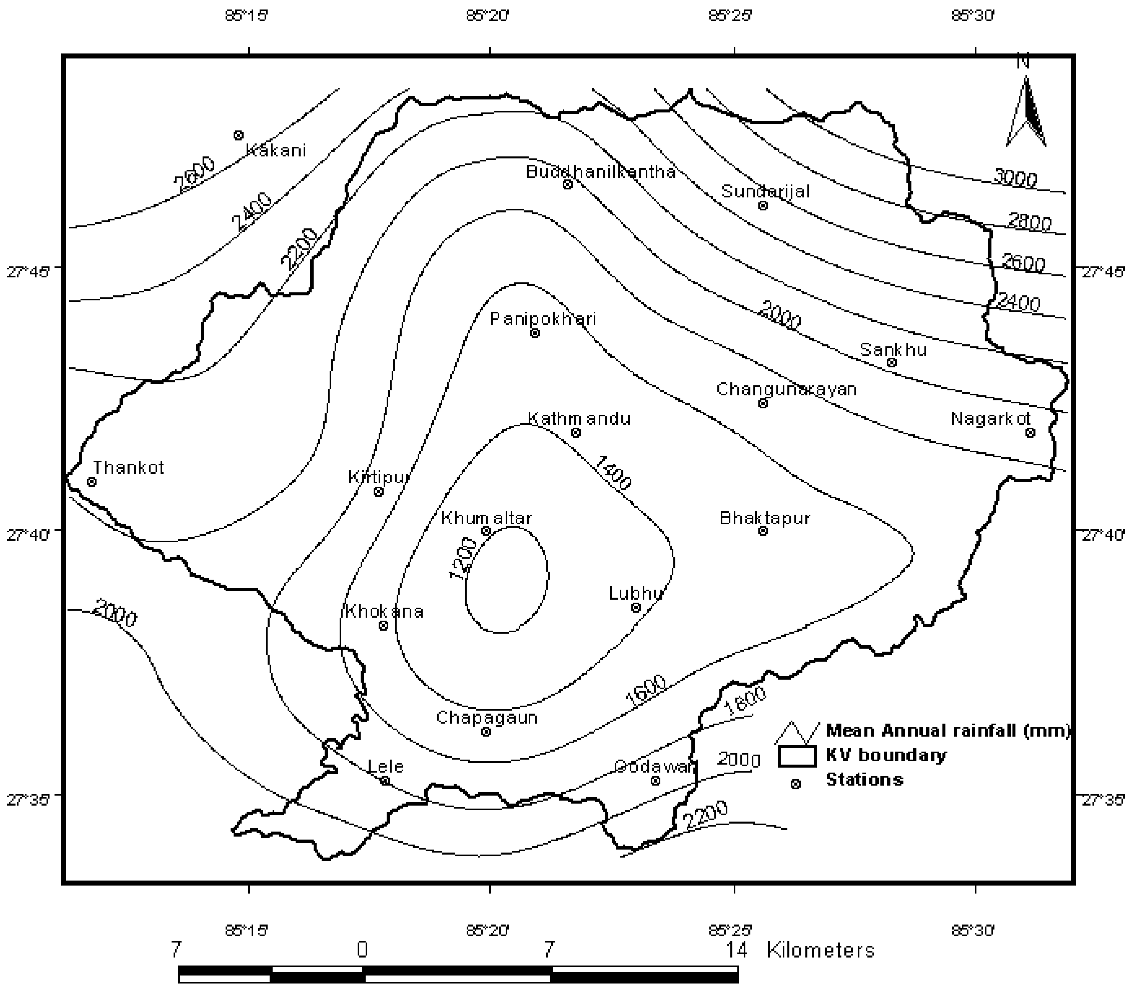


Figure 2 : Spatial pattern of Annual rainfall (mm) distribution in Kathmandu Valley

Dots: meteorological stations

(Source: Created from Devkota, L. P., SOHAM-Nepal, 2005 and DHM)

The relative humidity in January (minimum) ranges between 70% to 80% and that in July (maximum) is greater than 85%. Minimum temperature at the study area ranges from 0^0C to -4^0C. Similarly, Maximum temperature ranges from 26^0C to 30^0C. The average temperatures obtained from the recorded values from 1992 to 2001 at Kathmandu Airport, Khumaltar, Nagarkot, Godawari, Panipokhari and Buddhanilkantha are shown in the Table 2.

Table 2 : Average Temperature in ^{0}C of Kathmandu Valley computed from recorded data

Average of KV	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T_{max} (°c)	15.68	17.67	21.71	24.70	25.57	25.53	25.00	24.98	24.48	23.10	20.36	17.06
T_{min} (°c)	2.42	4.34	7.63	11.00	14.46	17.28	18.21	18.06	16.68	12.51	7.93	3.88
T_{mean} (°c)	9.05	11.00	14.67	17.85	20.01	21.40	21.60	21.52	20.58	17.81	14.14	10.47

(Source: DHM, 1992-2003)

4.4 LAND USE

The land use analysis of the Kathmandu valley region is intended to provide for an understanding of status of the ecological conditions both natural and man-made.

Table 3 : Major land use (1994) categories Kathmandu Valley

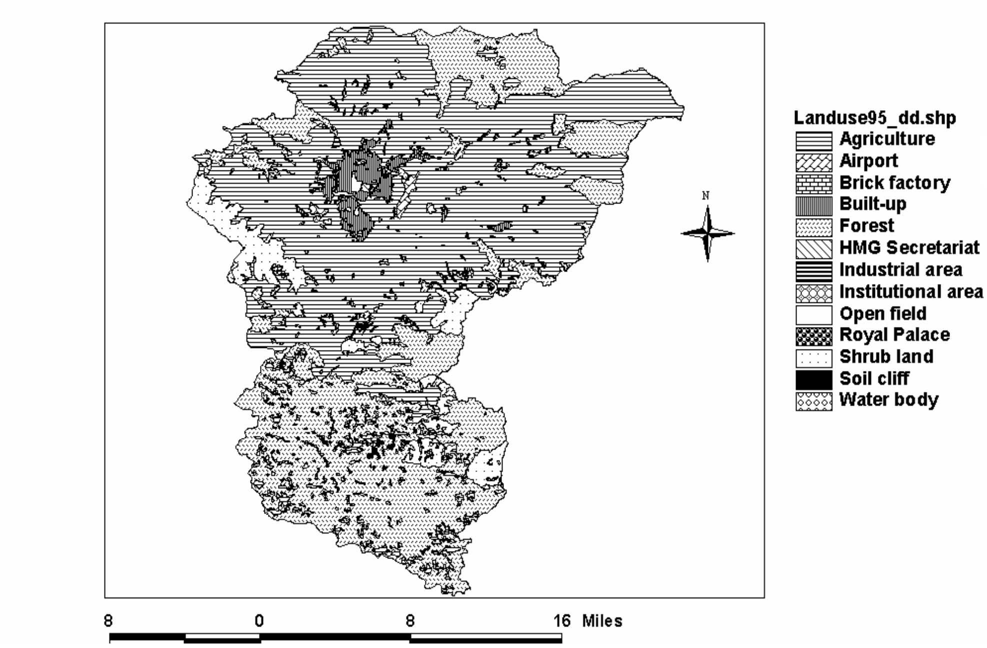
Categories	Area (Km^2)	Percent
Agriculture	421.8	64.3
Forest	203.2	31.0
Settlement Area	26.4	4.0
Sand, Gravel & Boulder	4.6	0.7
Total	**656**	**100**

Source: Stanley International Ltd, (1994) as cited in Pradhan (1998)

Table 4: Landuse (1995) of Kathmandu, Lalitpur and Bhaktapur districts

Categories	Area (Km^2)
Agriculture	509.88
Airport	2.28
Brick factory	0.31
Built-up	24.41
Forest	327.74
HMG Secretariat	0.41
Industrial area	0.38
Institutional area	1.45
Open field	1.37
Royal Palace	0.38
Shrub land	56.91
Soil cliff	1.13
Water body	0.39
Total	927.03

(Source: ICIMOD, 2000)



(Source: ICIMOD, 2000)

Figure 3 : Landuse (1995)

CHAPTER FIVE

5. MATERIALS AND METHODS

5.1 MATERIALS

5.1.1 Climatic Data

The required inputs to FAO Penman-Monteith (1998) ET model are temperature, solar exposure, sunshine hours, vapor pressures (relative humidity) and wind speed data. For the estimation of reference evapotranspiration data, available required input data of the stations within and close to the Kathmandu Valley were purchased from Department of Hydrology and Meteorology (DHM). The period of records varied from one station to another. The collected data and periods are as shown in Table 5.

Table 5 : Collected data

Station index	Station Name	Lat. (dms) N	Long. (dms) E	Elevation (m)	Collected data	Collected period	Source
1030	Ktm Airport	27 42 00	85 21 00	1336	→ Max. and Min Temperature	→ 1992 – 2002	→ DHM
					→ Sunshine hours	→ 1976 –1998	→ DHM Publ.
					→ RH	→ 1992 – 2002	→ DHM
					→ Wind speed	→ 1985 – 1986	→ DHM publ.
					→ Pan Evaporation	→ 1976 – 1982	→ DHM publ.
1022	Godawari	27 35 00	85 23 00	1400	→ Max. And Min Temperature	→ 1994 – 2003	→ DHM
					→ RH	→ 1994 – 2003	→ DHM
1071	Buddhanilkantha	27 47 00	85 21 00	1350	→ Max. And Min Temperature	→ 1992 – 2001	→ DHM
					→ RH	→ 1992 – 2001	→ DHM
1029	Khumaltar	27 40 00	85 20 00	1350	→ Max. and Min Temperature	→ 1992 – 2001	→ DHM
					→ RH	→ 1992 – 2001	→ DHM
					→ Wind speed	→ 1976 – 1986	→ DHM publ.
					→ Sunshine hours	→ 1976 – 1977	→ DHM publ
					→ Pan evaporation	→ 1976 – 1986	→ DHM publ.
1043	Nagarkot	27 42 00	85 31 00	2163	→ Max. And Min Temperature	→ 1992 – 2001	→ DHM
					→ RH	→ 1992 – 2001	→ DHM
					→ Wind speed	→ 1985 – 1986	→ DHM publ
1039	Panipokhari	27 44 00	85 21 00	1335	→ Max. And Min Temperature	→ 1995 – 2000	→ DHM
					→ RH	→ 1995 – 2002	→ DHM
1007	Kakani	27 48 00	85 15 00	2064	→ Sunshine hour	→ 1976 – 1980	→ DHM publ.
					→ Pan evaporation	→ 1976 – 1984	→ DHM publ.
					→ Wind speed	→ 1976 - 1979	→ DHM publ.

For the other stations considered in the study, the required data were generated by using the climatic models given by Nayava (2005) and by using multiple regression analysis of the collected data.

Similarly, long-term rainfall data of seventeen stations, collected from the DHM publication of climatic data and from Devkota (2005) were used to obtain the estimates of Cloud Cover using the climatic models.

5.1.2 Automatic Weather Station and Pan Evaporation data

The *automatic rainwise* instrument installed at the Department of Hydrology and Meteorology, Kritipur was used to get the direct measured data. The data of different parameters such as Solar radiation, Temperature, Relative Humidity, Wind speed etc. are recorded by this automatic rainwise instrument. The instrument helps to get the hourly data of each of the parameters. The recorded data of different climatic parameters have been depicted in the figures 4 to 9. The daily evaporation was measured from the evaporation pan installed at the Department of Hydrology and Meteorology using pan coefficient 0.8. The recorded data of Evaporation Pan from April 13th 2004 have been shown in figure 8.

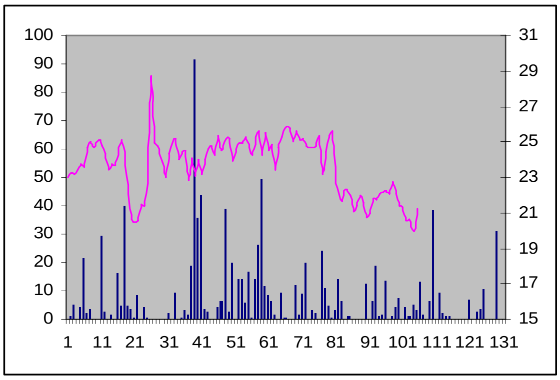


Figure 4: Rainfall/temperature

X axis: day; Y axis: rainfall, mm; Secondary Y axis: mean daily temperature, ^{0}C

Starting from June, 2004

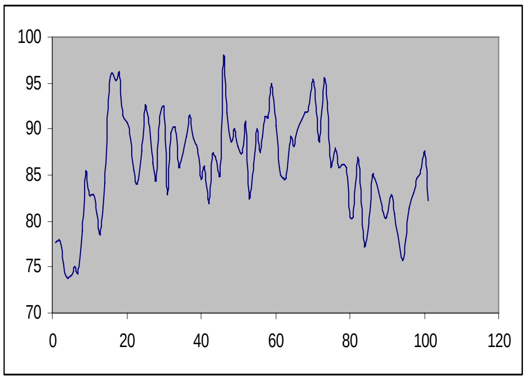


Figure 5: Humidity

X axis: Day Y axis: Humidity, %

Starting from June 2004

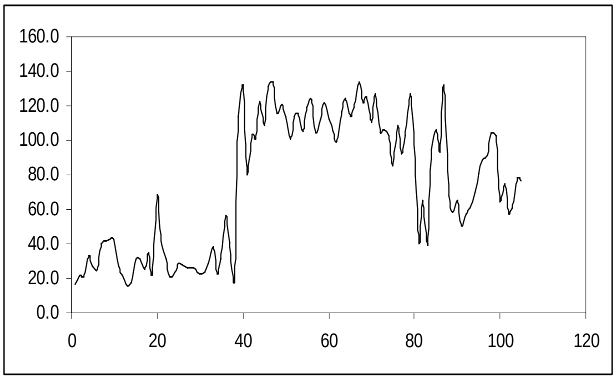


Figure 6: Wind speed

X axis: Day Y axis: wind speed, km/day

Starting from June 2004

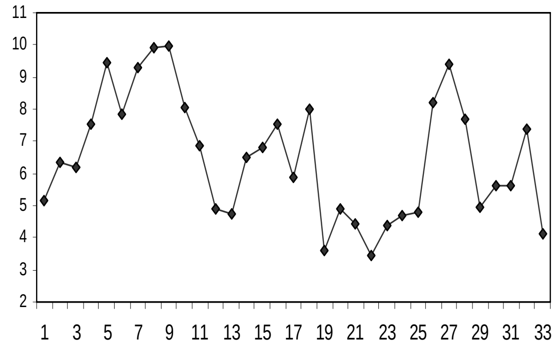


Figure 7 : Incoming radiation above the surface

X axis: Day Y axis: Solar radiation, mm/day starting from 19 June 2004

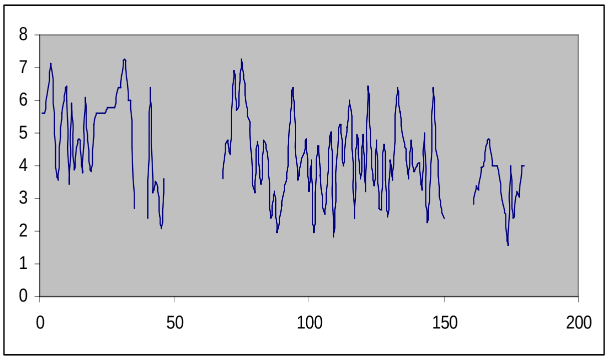


Figure 8 : Evaporation (Pan) starting from April, 2004

X-axis Days start from April 13th, Y-axis Evaporation in mm

(Source: Experimental data in alliance with Shrestha 2004)

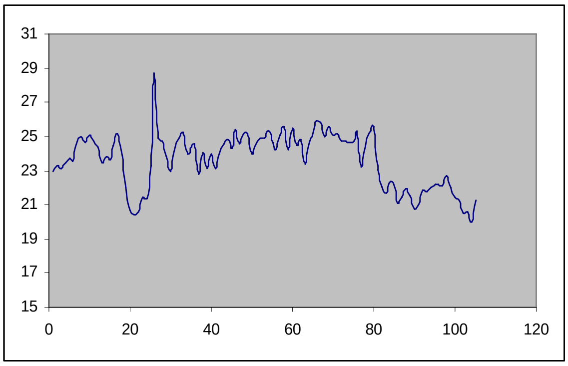


Figure 9 : Temperature record from June 2004

X axis: Day Y axis: temperature ,^{0}C

5.1.3 Digital Maps

For the mapping of ETo and radiation in GIS environment, Digital version of Kathmandu Valley boundary Map, contour map, land use map and land system map of the Kathmandu Valley were collected from ICIMOD.

Coordinate system used by ICIMOD is as follows:

Spheroid	:	Everest 1830
Projection	:	Universal Transverse Mercator
Central Meridian	:	84^0 E
Reference Latitude	:	26^0 15'N
False Easting	:	400,000 m
False Northing	:	0 m
Scale Factor	:	0.9999

This coordinate system was transformed to the coordinate system used by Topographical Survey Branch in topographical map (1:25000). Description of the coordinate system used in all the maps used in this study is as follows:

Spheroid	:	Everest 1830
Projection	:	Modified Universal Transverse Mercator
Central Meridian	:	840 E
Reference Latitude	:	00 N
False Easting	:	500,000 m
False Northing	:	0 m
Scale Factor	:	0.9999

5.1.4 Softwares:

1) Microsoft Excel spreadsheet

2) ArcView GIS 3.2a

5.2 METHODS

For the estimation of Radiation and Evapotranspiration, various climatological and physical parameters such as Sunshine hours, Temperature, Vapour pressures (relative humidity) and Wind Speeds are required. Synoptic and agro-climatic stations measure these parameters directly. Good measurements of these variables are very important for the better estimation of radiation and evapotranspiration. Some parameters can be derived with the help of a direct or empirical relationship to commonly measured data (if not available). This section deals with the computations of all the input data, relationships and procedures for estimating missing parameters and methods for the calculation of Radiation and Evapotranspiration by means of the FAO Penman-Monteith method.

5.2.1 Method for Estimating missing input climatic parameters

5.2.1.1 Air Temperature

Air temperature is the main parameter used for the reference evapotranspiration calculations.

The monthly data used to compute the ET terms were derived from daily measured data. Daily mean temperature was taken as the average of daily maximum and minimum temperatures. From maximum and minimum temperatures, the daily mean temperature is calculated as,

$$T_{Mean} = \frac{T_{min} + T_{max}}{2} \quad \text{....................} \; 1$$

The daily maximum and minimum temperatures for a month may be averaged to get the mean monthly maximum and minimum temperatures. From these monthly maximum and minimum temperatures for a particular month, mean monthly temperature for that month is calculated.

For the stations where observed data are not available, the mean monthly temperature, mean monthly maximum temperature and mean monthly minimum temperature data have been estimated from the multiple regression equation for Temperature derived from the collected data, that consider latitude, longitude and elevation as independent variables and temperature as the dependent variable.

With reference to collected data of maximum and minimum temperature of six stations (as mention in Table 5, the multiple regression analysis was carried out for all the stations considering station's latitude, longitude and elevation as independent variables and Temperature as dependent variables.

The regression equation developed is

$$y = A + B\,x + C\,x_1 + Dx_2 \text{ .... } 2$$

Where,

y = Mean monthly maximum or Mean monthly minimum temperature in ^{0}C;

x = latitude in degrees with minutes converted to decimals;

x_1 = longitude in degrees with minutes converted to decimals;

x_2 = elevation in meters: and

A, B, C and D are monthly constants

The monthly constants for each month and the coefficients of determination value (R^2) are shown in Appendix 4 and 5. The mean monthly maximum temperature, mean monthly minimum temperature and mean monthly temperature values for all the 12 months have been calculated for all the seventeen stations in the study area. All the estimated temperature values for 6 climatological stations were replaced by the recorded temperature, where available. The recorded and estimated temperature data were also compared and analyzed.

5.2.1.2 Sunshine Hours

A relationship between the ratio of actual sunshine hours (n) and possible sunshine hours (N) with the monthly rainfall has been established by Nayava (1981) and Pokhrel (1998). Hence, this empirical method is suitable to derive sunshine hours for whole Nepal. From the sunshine patterns in Nepal, whole country is tentatively divided into 10 sunshine groups depending on geographical location and the elevation. The appropriate group for Kathmandu valley is identified as Group 6 by locating the coordinates on the Sunshine group map Pokhrel (1998).

The equation used to derive n/N is

$$\frac{n}{N} = A + Bp + Cp^2 \text{ .... } 3$$

Where,

p = monthly precipitation in millimeters and

A, B and C are constants depending on the geographical location and the elevation of the site being analyzed.

The constants applicable to 10 sunshine groups are tabulated in Appendix 3. The monthly precipitation data of all 17 stations considered for study were taken from DHM publication of climatic records and from Devkota (2005).

5.2.1.3 Air Humidity /Vapour Pressures

The water content of the air can be expressed in several ways. In agro-meteorology, vapour pressure, dewpoint temperature and relative humidity are common expressions to indicate air humidity.

Saturation Vapor Pressure (e_s)

Air is said to be saturated when it cannot store any extra water molecules. The corresponding vapour pressure is called the saturation vapour pressure. As saturation vapor pressure is related to air temperature, it can be calculated from the air temperature. The relationship is expressed by:

$$e_s = 0.6108 \exp\left(\frac{17.27\,T}{T + 237.3}\right) \text{ .... } 4$$

e_s : saturation vapor pressure [kPa]

T : temperature [°C]

[Reference: FAO (1998)]

Due to the non-linearity of the above equation, the mean saturation vapor pressure for a day or month should be computed as the mean between the saturation vapor pressure at the mean daily maximum and minimum air temperatures for that period:

$$e_s = \frac{e_{(T_{max})} + e_{(T_{min})}}{2} \text{ .... } 5$$

Where $e_{(Tmin)}$ and $e_{(Tmax)}$ are the saturation vapour pressure at minimum and maximum temperatures.

Actual Vapor Pressure (e_a)

The actual vapour pressure (e_a) is the vapour pressure exerted by the water in the air. When the air is not saturated, the actual vapour pressure will be lower than the saturation vapour pressure. The difference between the saturation and actual vapour pressure is called the vapour pressure deficit or saturation deficit and is an accurate indicator of the actual evaporative capacity of the air.

e_a derived from relative humidity data

The actual vapour pressure can be calculated from the relative humidity. Depending on the availability of the humidity data, different equations should be used.

From RH_{max} and RH_{min}

$$e_a = \frac{e_{a(T_{min})} + e_{a(T_{max})}}{2} = \frac{1}{2}\left(e_{(T_{min})} \cdot \frac{RH_{max}}{100} + e_{(T_{max})} \cdot \frac{RH_{min}}{100}\right) \text{.....................} 6$$

Where,

e_a	=	actual vapour pressure [kPa] average daily vapour pressure
RH_{max}	=	maximum daily relative humidity [%]
T_{min}	=	minimum daily temperature [°C]
$e_{(Tmin)}$	=	saturation vapor pressure at T_{min} [kPa]
$e_{a(Tmin)}$	=	actual vapor pressure at T_{min} [kPa at early afternoon (around 14:00)
RH_{min}	=	minimum daily relative humidity [%]
T_{max}	=	maximum daily temperature [°C]
$e_{(Tmax)}$	=	saturation vapor pressure at T_{max} [kPa]
$e_{a(Tmax)}$	=	actual vapor pressure at T_{max} [kPa]

From RH_{mean}

Mean daily Relative Humidity is defined as follows:

$$RH_{mean} = \frac{RH_{max} + RH_{min}}{2} \text{.....................} 7$$

Where,

RH_{mean} : mean daily relative humidity.

In Nepal humidity data is recorded at 08:45 hours and 17:45 hours each day. The average of these two readings can be taken as the daily mean relative humidity and average of the daily figures for a month as the monthly mean (RH_{mean}).

Then, e_a is estimated as:

$$e_a = \frac{RH_{mean}}{100}\left[\frac{e_{(T_{max})} + e_{(T_{min})}}{2}\right] = \frac{RH_{mean} \times e_s}{100} \text{ .... 8}$$

However, above Equation for e_a is less desirable than other equations described below.

From RH_{max}

When RH data are in doubt, then only RH_{max} can be use as:

$$e_a = \frac{e_{(T\,min)} RH_{max}}{100} \text{ .... 9}$$

From dew point Temperature

As the dew point temperature is the temperature to which the air needs to be cooled to make the air saturated. The actual vapor pressure or average daily vapor pressure (e_a) is the Saturation Vapor Pressure at dew point temperature and can be determined from:

$$e_a = 0.611 \exp\left(\frac{17.27\, T_{dew}}{T_{dew} + 237.3}\right) \text{ .... 10}$$

When humidity data are lacking, an estimate of actual vapour pressure, e_a, can be obtained by assuming that dew point temperature (T_{dew}) is near the daily minimum temperature (T_{min}) [FAO,1998]. This statement implicitly assumes that at sunrise, when the air temperature is close to T_{min}, air is nearly saturated with water vapour and the relative humidity is nearly 100%. If T_{min} is used to represent T_{dew} then:

$$e_a = 0.611 \exp\left(\frac{17.27\ T_{min}}{T_{min} + 237.3}\right) \text{ .... 11}$$

FAO's method (1998) assumes that the dew point temperature is close to the minimum daily temperature and therefore uses this value for the estimation of the actual vapor pressure.

5.2.1.3 Wind Speed

Wind was classified as light, medium and strong wind due to the limited data (Nayava, 1981 as cited in Nayava, 2005). McDonald (1982, 1990) had done similar classification. WELINK (1998) had used only light wind in all the ETo Calculations in the Gandaki Water Basins study [ICIMOD, 2004]. Wind speed in the Kathmandu valley was only published for very few stations (Table 5).

There are many theoretical relations to compute the wind profile at different heights. To compute the wind speed values for all the 12 months, polynomial equation with the elevation (Pokhrel, 1998) is used. The wind equation is

$$y = A + A_1 E + A_2 E_2 \text{ .... 12}$$

Where,

y = wind speed in Km/day.

E = Elevation (meter); and

A, A_1 and A_2 = Appropriate monthly constants which are shown in Appendix 18.

Where wind speed records are taken at heights other than two meters above ground level, the correction factor need to be applied to the wind speed in km/day. The mean wind speed measured at some other height was transformed into a mean wind speed at 2 m according to the formula described in FAO (1998).

Measured 24 h windrun: u (km/day)

Height of Anemometer: h (m)

Wind conversion factor (u_{cf}):

- for h = 2 m; $u_{cf} = 1$
- for h > 2 m: $u_{cf} = (2/h) \times 0.17$
- for h < 2 m; $u_{cf} = (2/h) \times 0.22$

Converted 24 h windrun at 2 m above ground (u_2 in km/day):

$$u_2 = u_{cf} \times u$$

5.2.1.4 Statistical analysis (Standard Error of Estimation)

The standard error is a measure of the amount of error in the prediction values (y) for an individual measured values (x). The equation for the standard error of the predicted y is:

$$SEE = \sqrt{\frac{1}{(n-2)}\left[\sum (y-\bar{y})^2 - \frac{\left[\sum (x-\bar{x})(y-\bar{y})\right]^2}{\sum (x-\bar{x})^2}\right]} \quad \text{.....................} \ 13$$

where SEE is standard error of estimation, $\bar{x}$ and $\bar{y}$ are the sample means, and n is the sample size.

5.2.2 FAO Penman-Monteith equation

FAO Penman-Monteith equation is used for estimating ETo for its very convincing performance under varying climatic conditions. As the FAO Penman-Monteith equation has been used extensively worldwide, the method is used in this work.

The equation is written as:

$$ETo = \frac{0.408\,\Delta\,(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \quad \text{.....................} \ 14$$

Where, ETo = reference evapotranspiration [mm day^{-1}],

R_n = net radiation at the crop surface [MJ m^{-2} day^{-1}],

G = soil heat flux density [MJ m^{-2} day^{-1}] = 0 as G beneath the reference grass surface is relatively small; it may be ignored for 24-hour time steps.

T = air temperature at 2 m height [°C],

u_2 = wind speed at 2 m height [m s^{-1}],

e_s = saturation vapour pressure [kPa],

e_a = actual vapour pressure [kPa],

e_s-e_a = saturation vapour pressure deficit [kPa],

Δ = slope vapour pressure curve [kPa $°C^{-1}$],

γ = psychrometric constant [kPa $°C^{-1}$].

[Reference: FAO (1998)]

To compute the above equation various calculations required are mentioned below.

5.2.2.1 Slope Vapor Pressure Curve (Δ)

$$\Delta = \frac{4098\, e}{(T + 237.3)^2} \quad \text{.....................} \; 15$$

Δ : slope vapor pressure curve [kPa/°C]

T : air temperature [°C]

e : saturation vapor pressure at temperature T [kPa]

[Reference: FAO (1998)]

***5.2.2.2 Psychrometric Constant* (γ)**

$$\gamma = \frac{c_p P}{\varepsilon\lambda} \times 10^{-3} = 0.00163\frac{P}{\lambda} = 0.665 \times 10^{-3} P \quad \text{.....................} \; 16$$

γ = psychrometric constant [kPa $°C^{-1}$]

c_p = specific heat of moist air = 1.013 [kJ kg^{-1} $°C^{-1}$]

P = atmospheric pressure [kPa]

ε = ratio molecule. Weight water vapor/dry air = 0.622

λ = latent heat = 2.45 [MJ kg^{-1}]

[Reference: FAO, 1998]

Latent Heat of Vaporization (λ)

$$\lambda = 2.501 - (2.361 \times 10^{-3})\, T \quad \text{.....................} \; 17$$

Where,

λ = latent heat of vaporization [MJ kg^{-1}]

T = air temperature [°C]

[Reference: FAO (1998)]

As the value of the latent heat varies only slightly over normal temperature ranges a single value for lambda may be taken. For T = 20 °C

$\lambda = 2.45$ MJ kg^{-1}

Atmospheric Pressure (P)

Atmospheric pressure is related to elevation. It can be calculated by the relation

$$P = 101.3\left(\frac{293 - 0.0065z}{293}\right)^{5.26} \quad \text{.................... 18}$$

where,

P = atmospheric pressure [kPa]

Z = elevation above sea level [m]

5.2.2.3 Vapor pressure deficit (e_s - e_a)

The vapor pressure deficit is the difference between the saturation (e_s) and actual vapor Pressure (e_a) for a given time period. For time periods such as a week, ten days or a month e_s is computed from Equation 4 & 5. Using mean air temperature and not T_{max} and T_{min} in Equation 4 results in a lower estimate of e_s, thus in a lower vapor pressure deficit and hence an underestimation of the ETo.

Similarly e_a is computed with one of the equations from Eq.6 to 11. e_s and e_a for long time periods can also be calculated as averages of values computed for each day of the period.

5.2.2.4 Net Radiation (R_n)

The following parameters are required for the estimation of R_n (in equivalent unit of evaporation in mm).

$$R_n = R_{ns}\downarrow - R_{nl}\uparrow \quad \text{.................... 19}$$

Where,

R_n = net radiation [MJ m^{-2} d^{-1}]

R_{ns} = net incoming shortwave radiation [MJ m^{-2} d^{-1}]

R_{nl} = net outgoing longwave radiation [MJ m^{-2} d^{-1}]

5.2.2.5 Net Short-wave Radiation R_{ns}

The net shortwave radiation is the radiation received effectively by the crop canopy taking into account losses due to reflection:

$$R_{ns} = (1 - \alpha) R_s \approx 0.77 \ R_s \ \dots\dots\dots\dots\dots\dots\dots 20$$

Where,

α	=	albedo or canopy reflection coefficient = **0.23** overall average for grass
R_s	=	incoming solar radiation [MJ m^{-2} d^{-1}]

Solar intensity refers to the amount of solar energy that falls in unit time on a unit area, whose unit is MJ $m^{-2}d^{-1}$ or Watt m^{-2} or in terms of mm d^{-1} of equivalent evapotranspiration of water column. Solar intensity can be measured in the more advanced agro-meteorological stations with pyranometers or pyrheliometer. It requires, however, careful calibration and maintenance. Although electronic weather stations equipped with global pyranometers are becoming more widespread, measured solar radiation data may not be available from many agro-meteorological stations.

Short-wave radiation will in many cases be estimated from measured sunshine hours according to the following empirical relationship:

$$R_s = \left(a_s + b_s \frac{n}{N} \right) R_a \ \dots\dots\dots\dots\dots\dots\dots 21$$

Where,

a_s	=	fraction of extraterrestrial radiation (Ra) on overcast days ≈ 0.25 for average climate
$a_s + b_s$	=	fraction of radiation on clear days ≈ 0.75, i.e. $b_s \approx$ **0.50** for average climate
n/N	=	relative sunshine fraction
n	=	bright sunshine hours per day [hr]
N	=	total day length [hr]
R_a	=	extraterrestrial radiation [MJ m^{-2} d^{-1}]

Depending on atmospheric conditions (humidity, dust) and solar declination (latitude and month) the Angstrom values (a_s & b_s) will vary. When no actual solar radiation data are available and no calibration has been carried out for improved a_s and b_s parameters the following values are recommended for average climates:

$\mathbf{a_s = 0.25}$ $\mathbf{b_s = 0.50}$

For reference crop (grass),

$\boldsymbol{\alpha} \mathbf{= 0.23}$

Net short-wave radiation can thus be estimated according to the following general equation:

$$R_{ns} = 0.77 \; (0.25 \; + 0.50 \; \frac{n}{N}) \; R_a \; .... 22$$

R_a and N can be determined per month for given latitude using tabled value provided.

5.2.2.6 Net Longwave Radiation (R_{nl}):

Net long wave radiation is determined from the available temperature (T), actual vapor pressure (e_d) and the actual sunshine hours (n).

$$R_{nl} = f(T) \times f(e_a) \times f(n/N) \; .... 23$$

$$= \sigma T_k^4 \times \left(a + b\frac{n}{N}\right) \times (c - 0.044 \, e_a)$$

Where,

σ = Boltzman constant = 4.903×10^{-9} MJ K^{-4} m^{-2} day^{-1} = 2×10^{-9} mm K^{-4} day^{-1}

T_k = mean air temperature [K]

e_d = actual vapor pressure [mbar]

a, b, c are the empirical constant : a = 0.1, b = 0.9 and c = 0.34

n = actual bright sunshine hour

N = maximum possible sunshine hours

T = mean temperature in degree centigrade

e_a = actual vapor pressure in milli-bar

[Reference: FAO-24, Shakya B, 2004]

5.2.3 Determination of Evapotranspiration by Pan Evaporation Method

Actual evaporation from natural water, soil and crop surfaces is difficult to measure. Therefore, evaporation from artificial surfaces is empirically correlated to actual evaporation and evapotranspiration from natural surfaces. Evaporation pans are more widely used to measure the evaporation. Evaporation is determined by measuring the change in water level in the pan. The standard recommended pan is the class A pan. It is 25.4 cm deep with diameter of 120 cm (Shrestha, 1998). It is raised 15cm above the ground with wooden supports to allow free air circulation below the pan. Evaporation is measured at the interval of 24 hour. The water level is measured with hook gauge placed in stilling well within a pan or a measuring scale is used to measure the level decreased in the pan from its initial point.

Pan evaporation data can be used to estimate evapotranspiration as it is a measure of the combined effects of radiation, wind, temperature and humidity on evaporation from specific open water surface. The physical differences between pan and grass make adjustments necessary. Therefore, an adjustment factor is necessary to relate pan evaporation to evapotranspiration. The relation is expressed as,

$ET = K \times E$..................... 24

ET = mean daily evapotranspiration for the period

E = mean daily pan evaporation for the period [mm/day]

K = adjustment factor for class A pan (generally taken as 0.8)

5.3 ETo Determination Framework

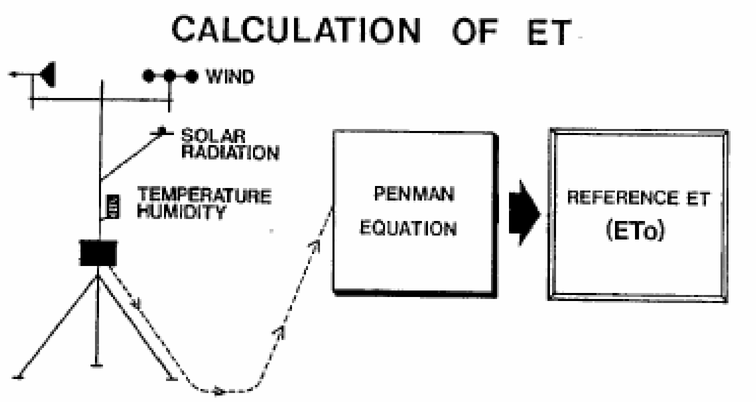


Figure 10 : Weather station; schematic depicting how ETo is determined

Wind, solar radiation, temperature and humidity data from an automatic weather station are used as input to the Penman Equation, which in turn, provides the ETo value.

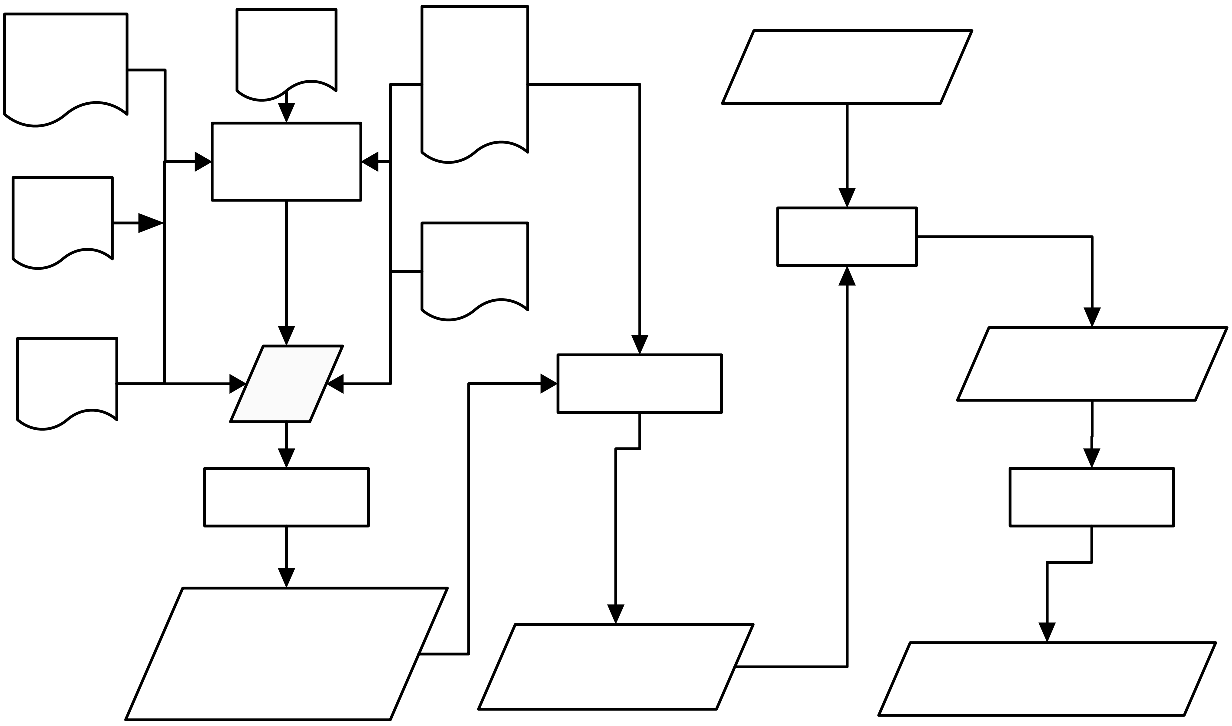


Figure 11 : Process Model

Table 6 : Calculation sheet of Reference Evapotranspiration (ETo)

Parameters		
T_{Max} _______ [^{0}C], T_{Min} _______ [^{0}C]	$T_{Mean} = \frac{T_{min} + T_{max}}{2}$	___________ [^{0}C]
Altitude __[m], Pressure ___ [kPa]	Calculate γ	__________ [kPa/ ^{0}C]
T_{mean} _______ [^{0}C]	Calculate Δ	__________ [kPa/ ^{0}C]
Altitude_____[m]	u_2 _________ km/day	__________ m/s
Vapour Pressure Deficit:		
T_{Max} _______ [^{0}C]	Calculate $e_{(Tmax)}$	___________ [kPa]
T_{Min} _______ [^{0}C]	Calculate $e_{(Tmin)}$	___________ [kPa]
Saturation Vapour Pressure	$e_s = \frac{e_{(T_{max})} + e_{(T_{min})}}{2}$	___________ [kPa]
Actual vapour pressure e_a derived from mean humidity:		
RH_{mean} _______ [%]	$e_a = \frac{e_s \times RH_{mean}}{100}$	__________ [kPa]
OR ea derived dewpoint Temperature as minimum Temperature:		
$T_{dew} \approx T_{min}$ _______ [^{0}C]	$e_a = e_{(Tdew)}$	__________ [kPa]
Vapour pressure deficit	**(e_s - e_a)**	__________ [kPa]
Radiation:		
Lat. ________	Read N	________ [hr]
Month _________	Read R_a	________ [mm/day]
n ______ [hr]	R_S = (0.25+0.50n/N) R_a	________ [mm/day]
α = 0.23	R_{ns} = (1-α) R_S	________ [mm/day]
T_{mean} ____ [^{0}C]	Read f (T) f(e_a) f (n/N)	
e_a________ [kPa]	R_{nl} =f (T) .f (e_a).f (n/N)	________ [mm/day]
$R_n = R_{ns} - R_{nl}$		________ [mm/day]
Grass Reference Evapotranspiration:		
assuming G = 0, $ETo = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$		______ mm/day

5.4 GIS (Geographic Information system) Application

5.4.1 Preparation of Maps

Elevation as well as latitude and longitude were used as explanatory variables to take into account the variation of solar radiation components and Reference Evapotranspiration at seventeen different stations over Kathmandu Valley.

Kathmandu Valley Boundary

Polygon map or shapefile of the Kathmandu Valley boundary has been projected to appropriate coordinate system and imported to view.

Point map of the Stations

From the latitude and longitude of the stations, a point map was created. The latitude and longitude were noted from climatological publications and the locations of stations were plotted in digital map with the coordinate system used by Department of survey.

GIS Database development

The point estimated monthly values of solar radiation and net radiation in W/m^2 for all the selected stations along with their latitude, longitude and altitude were imported in GIS database format. Likewise, the point estimated total monthly Evapotranspiration values in mm were imported in GIS database.

R_s (incoming shortwave radiation) and R_n (Net radiation) isoline maps

The incoming solar radiations and net radiations in W/m^2 for each months of a year were plotted in the point map over the latitudes of the study area creating isolines (contours). The map was clipped by the valley boundary to extract only the study area.

Evapotranspiration Maps from point interpolation

A point interpolation performs an interpolation on randomly distributed point values and returns regularly distributed point values. This is also known as gridding. For each variable, there is one mean annual map and twelve mean monthly maps. The gridded data were then displayed using different representations using the map creation tools within the GIS software. Hence, the monthly maps of estimated Monthly evapotranspiration data in mm/month at seventeen stations of study area were created using isolines method and point interpolation tool provided in ArcView GIS software.

CHAPTER SIX

6. ANALYSIS

The main objective of research is estimation and mapping of Solar radiation and Reference Evapotranspiration (ETo). This chapter deals with the same. Firstly, Solar radiation (R_s) and Net radiation (R_n) data were computed for all seventeen stations using the method suggested by Allen (1998). Then, ETo data were computed using FAO Penman-Monteith Equation (1998) and the estimated data were compared with the available literature data.

6.1 Determination of Solar Radiation (R_S) & Net Radiation (R_n)

Data such as Global Extraterrestrial Radiation (R_a), Sunshine hours, Temperature, Air Vapour pressures or humidity are required for the estimation of incoming Solar radiation (R_s) and Net radiation (R_n). Analysis of Measured and Estimated data of these climatic parameters are summarized in the following sub heads.

6.1.1 Cloud cover or Sunshine Hours

Records of sunshine hours used for the study were from three climatic stations at Kathmandu Airport, Khumaltar and Kakani. Highest actual sunshine hours were recorded during March, April and May months. The ratio of recorded mean monthly sunshine hours to the maximum (global) sunshine hour showed high amount of cloud cover during monsoon season. The recorded data of sunshine hours were available for only three stations and of short period hence error may arise while taking the average for whole Kathmandu valley.

For the stations that do not record the sunshine hour, the ratio of actual sunshine hour to maximum sunshine hours could be derived from rainfall record using Equation 3. The monthly and annual rainfall data used for the estimation are presented in Appendix 2. The estimated monthly n/N values of seventeen stations are presented in Table 7.

The estimated and the recorded sunshine hours for Kathmandu Airport, Khumaltar and Kakani stations are close to each other. Thus, the estimation model (Equation 3) can be considered as good estimator of ratio of actual to maximum sunshine hours. The Global Maximum sunshine hour and estimated average actual sunshine hour of Kathmandu valley are summarized in the Table 8.

Table 7 : Estimated n/N at different stations of Kathmandu Valley

Stn Index	Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1007	Kakani	0.750	0.731	0.696	0.629	0.442	0.369	0.650	0.691	0.332	0.609	0.767	0.751
1015	Thankot	0.742	0.730	0.697	0.626	0.501	0.340	0.425	0.371	0.344	0.625	0.760	0.738
1022	Godavari	0.752	0.736	0.706	0.659	0.526	0.338	0.413	0.351	0.362	0.634	0.766	0.739
1029	Khumaltar	0.755	0.747	0.728	0.666	0.571	0.414	0.341	0.377	0.486	0.671	0.775	0.745
1030	Ktm Airport	0.756	0.747	0.717	0.659	0.546	0.368	0.331	0.339	0.442	0.659	0.770	0.753
1035	Sankhu	0.761	0.730	0.720	0.662	0.498	0.334	0.432	0.421	0.353	0.642	0.763	0.760
1039	PaniPokhari	0.756	0.747	0.716	0.632	0.535	0.363	0.331	0.331	0.435	0.657	0.769	0.758
1043	Nagarkot	0.759	0.747	0.719	0.661	0.507	0.333	0.372	0.370	0.368	0.620	0.765	0.760
1052	Bhaktapur	0.758	0.743	0.717	0.663	0.511	0.362	0.331	0.332	0.442	0.662	0.774	0.752
1059	Changunarayan	0.752	0.738	0.711	0.650	0.497	0.358	0.343	0.336	0.402	0.646	0.767	0.752
1060	Chapagaon	0.752	0.747	0.716	0.671	0.578	0.378	0.335	0.338	0.422	0.667	0.777	0.743
1061	Lubhu	0.751	0.754	0.736	0.627	0.555	0.423	0.330	0.344	0.467	0.646	0.753	0.727
1071	Buddhanilkantha	0.744	0.740	0.692	0.657	0.505	0.332	0.546	0.364	0.363	0.615	0.746	0.744
1073	Khokana	0.752	0.744	0.719	0.656	0.562	0.386	0.331	0.344	0.427	0.658	0.771	0.744
1074	Sundarijal	0.748	0.728	0.688	0.615	0.422	0.335	0.638	0.579	0.332	0.619	0.760	0.745
1075	Lele	0.746	0.741	0.676	0.636	0.547	0.351	0.359	0.355	0.409	0.716	0.659	0.773
KV	**Average**	**0.752**	**0.741**	**0.710**	**0.648**	**0.519**	**0.361**	**0.407**	**0.390**	**0.399**	**0.647**	**0.759**	**0.749**

(Source: computed using Eq. 3)

Table 8 : Sunshine hours of Kathmandu valley

Parameters	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Global maximum sunshine hours N	10.36	11.11	11.96	12.86	13.61	14.01	13.83	13.19	12.36	11.44	10.61	10.13
Estimated actual Sunshine hours (n)	7.80	8.23	8.48	8.33	7.07	5.06	5.58	5.10	4.93	7.41	8.05	7.59

(Source: Shakya, 2004 and computed from Table 7)

6.1.2 Solar Radiation (R_s)

Global Extraterrestrial Radiation (R_a), in millimeters per day equivalent evapotranspiration, corresponding to the latitude of the place and time of year, can be obtained from the standard climatic tables. From the values of n/N and R_a, Solar radiation at the top of the ground was estimated by using Equation 20 as illustrated in the calculation sheet (Table 6). The estimated solar radiation data at the top of ground in watt/m^2 for seventeen stations have been presented in Table 9.

The average R_s measured from automatic rain-wise instrument installed at T.U. in June and July were 7.63 mm/day and 5.84 mm/day respectively (figure 7), whereas, the estimated solar radiation at Kirtipur was 7.22 mm/day in Jun and 7.09 mm/day in July. The values were very close for June but for July, the equation seems to overestimate the solar radiation. As the recorded data was only of single year, error may be there in recorded data itself. However, the estimated solar radiation values are considered to be close to the actual solar radiation. Therefore, the equation used is considered to be good estimator.

Table 9 : Mean monthly Solar radiation (R_s) in mm/day at different stations of Kathmandu Valley

Stn Index	Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Mean
1007	Kakani	5.69	6.83	7.83	8.89	7.86	7.46	9.74	9.95	6.00	6.54	6.10	5.36	7.35
1015	Thankot	5.78	6.95	8.08	8.67	8.26	7.10	7.73	6.88	5.99	6.81	6.24	5.45	6.99
1021	Kirtipur	5.82	7.01	8.16	8.79	8.45	7.22	7.09	6.58	6.36	6.99	6.23	5.48	7.01
1022	Godawari	5.69	6.94	8.08	9.00	8.64	7.11	7.49	6.78	6.15	6.91	6.19	5.39	7.03
1029	Khumaltar	5.79	7.02	8.23	8.99	8.96	7.71	7.00	6.95	6.97	6.97	6.23	5.41	7.19
1030	Ktm Airport	5.82	7.02	8.14	8.97	8.60	7.35	6.93	6.61	6.65	6.94	6.20	5.47	7.06
1035	Sankhu	5.86	6.95	8.24	8.95	8.23	7.05	7.79	7.27	6.06	6.91	6.25	5.55	7.09
1039	Panipokhari	5.81	7.04	8.09	8.59	8.74	7.33	6.94	6.58	6.64	6.93	6.17	5.50	7.03
1043	Nagarkot	5.78	7.01	8.04	8.91	8.29	7.03	8.74	6.83	6.12	6.74	6.17	5.47	7.09
1052	Bhakatapur	5.85	7.02	8.22	8.96	8.34	7.29	6.94	6.58	6.69	7.03	6.31	5.51	7.06
1059	Changunarayan	5.76	6.93	8.12	8.86	8.22	7.25	7.04	6.61	6.40	6.88	6.21	5.44	6.98
1060	Chapagaun	5.82	7.04	8.21	9.02	8.90	7.42	6.97	6.62	6.55	7.06	6.32	5.47	7.12
1061	Lubhu	5.82	7.08	8.34	8.68	8.71	7.80	6.93	6.67	6.87	6.93	6.20	5.40	7.12
1071	Buddhanilkantha	5.78	6.95	8.07	8.76	8.06	7.05	7.48	6.90	6.16	6.85	6.22	5.45	6.98
1073	Khokana	5.82	7.03	8.23	8.90	8.76	7.49	6.94	6.66	6.58	7.01	6.29	5.47	7.10
1074	Sundarijal	5.74	6.88	7.96	8.59	7.61	7.05	9.50	8.52	5.90	6.72	6.17	5.41	7.17
1075	Lele	5.79	7.01	7.94	8.75	8.64	7.19	7.18	6.75	6.45	7.36	5.74	5.60	7.03
KV	**Average**	**5.79**	**6.98**	**8.12**	**8.84**	**8.43**	**7.29**	**7.55**	**7.04**	**6.38**	**6.92**	**6.19**	**5.46**	**7.08**

(Source: Computed from Eq.21)

6.1.3 Temperature

From the recorded temperature data of six stations of the Kathmandu valley from 1992 to 2001, slight increasing trend was observed over the period. Mean annual temperatures in this period were about 18^0C to 19^0C at the valley floor and about 14.5^0C to 15.5^0C at Nagarkot, the higher elevation station considered for the study. From the temperature data of last 10 years, it is observed that mean monthly maximum temperature is increasing and mean monthly minimum temperature is decreasing. The highest maximum temperatures are measured in May to June months, in the pre-monsoon season, although the highest mean daily temperatures are usually observed in the monsoon season. This is mainly due to the increased cloud cover during the rainy season. In the pre-monsoon season cloud cover often breaks up and allows full sunshine and heating up the air. The temperature records of Kathmandu valley show great inter-annual variability.

Temperature is also recorded from April 13^{th} 2004 to October 9^{th} 2004 at CDHM / T.U. Mean temperature is around 23 ^{0}C. Extreme maximum temperature of 33.7 ^{0}C was recorded on April 15^{th} 2004 (Shrestha, 2004). The mean daily temperature along with rainfall hyetograph is depicted in figure 4. It indicates rise in temperature before the start of monsoon. Temperature drops considerably after monsoon due to decrease in latitudinal heating. But mean wind run and humidity increases from active start of monsoon.

To get the Maximum, Minimum and Mean monthly temperatures of the non recording stations, the multiple regression analysis was done from the records of six stations (Equation 2). The estimated maximum, minimum and mean temperature data of seventeen stations in ^{0}C have been shown in Appendix 9, 10 and 11. The estimated average maximum, minimum and mean monthly temperatures of Kathmandu valley have been summarized in Table 10. The Standard errors of estimations for each month calculated from the recorded values of six temperature recording climatic stations are shown below in Table 11. The estimated and recorded average temperatures at those six stations are very close.

Table 10 : Estimated Average Temperature in ^{0}C of Kathmandu Valley

Average of KV	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T_{max} (^{o}c)	15.98	18.01	22.73	25.42	26.15	26.68	26.55	27.34	25.56	24.13	21.44	17.53
T_{min} (^{o}c)	2.64	4.52	7.82	11.14	14.38	17.11	18.01	17.86	16.44	12.42	7.97	4.07
T_{mean} (^{o}c)	9.05	11.01	14.63	17.79	19.83	21.13	21.34	21.25	20.27	17.58	13.98	10.39

(Source: Computed from multiple regression analysis [Eq.2])

Table 11 : Standard Error of estimation of temperature for six recording stations

Parameter	Standard Error of Estimation in ^{0}C for the month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tmax	1.09	1.22	1.29	1.56	1.24	1.23	1.02	0.91	1.06	1.25	1.30	1.07
Tmin	0.48	0.27	0.36	0.34	0.58	1.05	1.15	1.11	0.99	0.60	0.36	0.35
Tmean	0.32	0.25	0.23	0.38	0.80	1.16	1.12	1.08	1.13	0.87	0.62	0.36

(Source: computed from Eq.13)

The standard error of estimation of maximum temperature was generally 1^{0}C and for the minimum and mean temperature was generally 0.5 ^{0}C. These errors are due to the omission of slope aspect, vegetation in the regression equation. It should be pointed out that the estimated temperature values were not corrected further as the variations did not cause a major change in the final computed ETo value.

6.1.4 Vapour Pressures

Saturated Vapour pressure

Saturation vapour pressure is calculated from the relation with temperature (Equation 4). The calculation procedure of Saturation vapour is illustrated in the calculation sheet (Table 6). Using mean air temperature instead of daily minimum and maximum temperatures results in lower estimates for the mean saturation vapor pressure. The corresponding vapor pressure deficit will also be smaller and the result will be some under-estimation of the reference evapotranspiration. Therefore, the mean saturation vapor pressure should be calculated as the mean between the saturation vapor pressure at both the daily maximum and minimum air temperature (Equation 5). Maximum and minimum temperature data used for the calculation are presented in the Appendix 9, 10 and 11. The average saturated vapour pressure in kPa of Kathmandu Valley calculated from the values of seventeen stations is presented in Table 13.

Actual Vapour Pressure

The procedure of calculation of Actual vapour pressures from the relative humidity is illustrated in the calculation sheet (Table 6). In the study area, only six stations, namely Kathmandu Airport, Khumaltar, Nagarkot, Panipokhari, Buddhanilkantha and Godawari, have records of Relative humidity. These humidity data were used for the calculation of actual vapour pressure and hence vapour pressure deficit for those stations. Relative humidity measured at CDHM / T.U. during experiment period was 78.83 % in June and 88.05 % in July (figure 5). The average relative humidity in % taken from the six recording stations is shown in Table 12.

Table 12 : Relative humidity (in %) of Kathmandu valley

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual average
Recorded humidity %	82.00	79.73	71.80	68.19	75.96	84.00	88.29	88.60	87.68	84.98	82.86	83.24	81.30

(Source: DHM, 1992-2003)

For the stations that do not record the relative humidity, the actual vapour pressure is estimated from the relation with minimum monthly temperature (Equation 11) as reported in Allen et. al. (1998). The minimum temperature of the stations have already been estimated and presented in Appendix 10. The average saturated and actual vapour pressures over Kathmandu valley for each month have been summarized in Table 13.

Table 13 : Saturated vapour pressure (e_s) and actual vapour pressure (e_a) in kPa of Kathmandu valley

Parameters	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
average e_s	1.27	1.45	1.88	2.26	2.50	2.70	2.73	2.77	2.55	2.20	1.79	1.40	2.13
average e_a	1.04	1.15	1.35	1.54	1.90	2.26	2.40	2.45	2.23	1.87	1.48	1.17	1.74

(Source: computed from Eq.4,5 and 11)

The error resulting due to consideration of mean relative humidity and assumption of minimum temperature as dew temperature is a very less in the (maximum of ±0.2 mm) in daily reference evapotranspiration, which totals approximately 6 mm per month at most (Merz, 2004).

6.1.5 Net Radiation (R_n)

Albedo for the reference grass was taken as 0.23 for the whole estimation process. Net radiation of each month for seventeen stations of Kathmandu valley was calculated by using the set of equations from Equation 19 to 23 as illustrated in calculation sheet (Table 6). The all necessary input parameters for the estimation of Net radiation have been analyzed above. The estimated R_n in mm/day for all the stations of Kathmandu valley has been presented in Table 14.

Table 14 : Net radiation (R_n) in mm/day at different stations of Kathmandu Valley

Stn Index	Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual mean
1007	Kakani	1.52	2.41	3.25	4.04	3.97	3.91	4.63	4.45	2.93	2.48	1.65	1.22	3.04
1015	Thankot	1.51	2.41	3.28	3.92	4.05	3.76	3.93	3.49	2.91	2.51	1.65	1.23	2.89
1021	Kirtipur	1.49	2.39	3.28	3.94	4.10	3.80	3.72	3.39	2.99	2.53	1.64	1.21	2.87
1022	Godawari	1.48	2.37	3.26	4.00	4.16	3.76	3.85	3.45	2.94	2.52	1.64	1.20	2.89
1029	Khumaltar	1.48	2.38	3.29	3.99	4.25	3.95	3.70	3.50	3.14	2.52	1.63	1.20	2.92
1030	Ktm Airport	1.48	2.37	3.26	3.98	4.14	3.84	3.67	3.40	3.06	2.52	1.63	1.20	2.88
1035	Sankhu	1.52	2.40	3.33	4.02	4.06	3.77	3.97	3.62	2.94	2.56	1.68	1.24	2.93
1039	Panipokhari	1.48	2.38	3.25	3.88	4.18	3.83	3.67	3.39	3.06	2.52	1.63	1.20	2.87
1043	Nagarkot	1.57	2.48	3.35	4.06	4.13	3.79	4.33	3.53	2.99	2.59	1.74	1.30	2.99
1052	Bhakatapur	1.50	2.39	3.31	4.01	4.08	3.83	3.69	3.40	3.09	2.56	1.67	1.23	2.90
1059	Changunarayan	1.47	2.37	3.28	4.00	4.06	3.83	3.73	3.42	3.03	2.52	1.64	1.20	2.88
1060	Chapagaun	1.51	2.40	3.31	4.02	4.25	3.87	3.70	3.42	3.06	2.57	1.68	1.24	2.92
1061	Lubhu	1.50	2.40	3.33	3.92	4.19	4.00	3.68	3.43	3.13	2.54	1.66	1.23	2.92
1071	Buddhanilkantha	1.43	2.33	3.22	3.93	3.98	3.74	3.85	3.49	2.94	2.47	1.59	1.15	2.84
1073	Khokana	1.47	2.37	3.28	3.96	4.18	3.87	3.67	3.41	3.04	2.52	1.63	1.20	2.88
1074	Sundarijal	1.47	2.36	3.23	3.92	3.86	3.76	4.52	3.99	2.90	2.48	1.62	1.18	2.94
1075	Lele	1.52	2.42	3.26	3.95	4.18	3.80	3.77	3.46	3.04	2.63	1.66	1.25	2.91
KV	**Avreage**	**1.49**	**2.39**	**3.28**	**3.97**	**4.11**	**3.83**	**3.89**	**3.54**	**3.01**	**2.53**	**1.65**	**1.22**	**2.91**

(Source: Computed from Eq.19 to 23)

Annual average Net radiation (R_n) over Kathmandu valley is 2.93 mm/day (7.18 MJoule/m^2/day). Maximum radiation (R_n) of 4.12 mm/day (10.1 MJoule/m^2/day) is estimated in the month of May and Minimum of 1.24 mm/day (3.04 MJoule/m^2/day) is estimated in the month of December. The net solar radiation calculated from the measured input parameters for the month of June and July at CDHM / T.U. are 4.83 mm/day and 3.56 mm/day respectively whereas the values for Kirtipur station are estimated to be 3.80 mm/day in June and 3.72 mm/day in July. This shows that the estimated values and calculated values from measured input parameters are close to each other and hence, the estimated values tend to the actual values.

*6.2 DETERMINATION OF REFERENCE EVAPOTRANSPIRATION (*ETO*)*

The meteorological factors determining evapotranspiration are weather parameters which provide energy for vaporization and remove water vapour from the evaporating surface. The principal weather parameters to consider are Air Temperature, Air humidity, solar radiation (sunshine), Wind speed (Allen et. al. 1998). The FAO Penman-Monteith equation to estimate the Reference crop Evapotranspiration from meteorological data (Equation 14) requires some atmospheric parameters and these four climatological parameters. The use of Penman method in Nepal is limited due to the scarcity of required meteorological records. However, use of extrapolated models based on the work of Nayava (1981), Pokhrel (1998), TAHAL Consulting

2002) can overcome this limitation. The models derive the estimates of temperature, Vapour pressure deficit and wind speed for sites where required data are not available (McDonald, 1982). For the determination of ETo, the required input climatological data of air temperature, vapor pressures (air humidity), wind speeds and Net Solar radiation and necessary atmospheric parameters are discussed in the following sub heads.

6.2.1 Air Temperature

The data of Air temperature have been discussed above in section 6.1.3. The temperature data of seventeen stations used for computation have been presented in Appendix 9, 10 and 11.

6.2.2 Air humidity

The humidity data, expressed as saturation vapour pressure and actual vapour pressure, have already been discussed in section 6.1.4. The saturated and actual vapour pressures of seventeen stations have been presented in Appendix 12 and 13.

6.2.3 Net radiation

Equation 19 to Equation 23 have been applied to compute the net radiation data at seventeen selected stations for every month of the year and the average monthly net radiations over whole Kathmandu valley have been summarized above in section 6.1.5. The data of net radiation at seventeen stations have been presented in Table 14.

6.2.4 Wind Speed

The wind speed, recorded at only four stations namely, Kakani, Kathmandu airport, Khumaltar and Nagarkot, were considered for the study. Also, the wind speed was measured at CDHM / Kirtipur for six months (figure 6). In Kathmandu valley, Maximum wind speed is observed in the month of April and Minimum is in the month of September. To obtain the wind speed at all the stations considered for the study, the second degree equation of wind speed with the elevation (in meter) [Equation 12] has been used.

From the analysis of the recorded and estimated wind speed data at the Kakani, Kathmandu Airport, Khumaltar and Nagarkot stations, the standard errors of estimation for each month were calculated (Table 15). The estimated values seemed to be lesser than measured particularly at higher elevations. Nevertheless, the estimated wind speed could be considered to be fairly close to the actual wind speed.

Table 15 : Standard error of Estimation of wind speed at four recording stations

Standard Error of Estimation of wind speed in m/s for the month											
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0.21	0.29	0.30	0.22	0.22	0.31	0.36	0.24	0.35	0.21	0.17	0.17

(Source: computed from Eq.13)

From the estimated data, it is found that the average annual wind run was found to be 1.14 m/s (117.43 Km/day) whereas average maximum monthly run of about 1.58 m/s (162.03 km/day) was found in the month of April and lowest 0.89 m/s (91.22 km/day) in September. Wind speed increases with the elevation. Maximum wind speed is at Nagarkot at 2163 m height and minimum is at Khokana at the lowest height. The wind speed data at all the seventeen stations and the average values have been presented in the Table 16.

Table 16 : Estimated monthly mean wind speed at 2 m height (m/s) at different stations

Stn Index	Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Mean
1007	Kakani	1.51	1.83	2.17	2.01	2.07	1.68	1.49	1.35	1.33	1.26	1.20	1.26	1.60
1015	Thankot	1.22	1.39	1.73	1.78	1.65	1.48	1.13	1.21	1.11	1.21	1.23	1.22	1.36
1021	Kirtipur[1]	0.89	1.05	1.36	1.45	1.33	1.08	0.76	0.81	0.76	0.87	0.88	0.87	1.01
1022	Godawari	0.93	1.10	1.41	1.49	1.37	1.13	0.81	0.85	0.80	0.91	0.92	0.92	1.05
1029	Khumaltar	0.87	1.04	1.34	1.43	1.31	1.06	0.75	0.79	0.74	0.86	0.86	0.86	0.99
1030	K.A.[2]	0.86	1.02	1.33	1.42	1.30	1.05	0.73	0.77	0.73	0.84	0.84	0.84	0.98
1035	Sankhu	0.99	1.15	1.47	1.54	1.42	1.19	0.87	0.92	0.86	0.97	0.98	0.98	1.11
1039	Panipokhari	0.86	1.02	1.33	1.42	1.30	1.04	0.73	0.77	0.73	0.84	0.84	0.84	0.98
1043	Nagarkot	1.63	1.97	2.34	2.15	2.21	1.79	1.58	1.43	1.41	1.35	1.29	1.36	1.71
1052	Bhakatapur	0.85	1.02	1.32	1.41	1.29	1.04	0.73	0.76	0.72	0.84	0.84	0.84	0.97
1059	Changu[3]	1.11	1.27	1.60	1.66	1.53	1.34	1.00	1.06	0.98	1.09	1.10	1.10	1.24
1060	Chapagaun	0.99	1.15	1.47	1.54	1.42	1.19	0.87	0.92	0.86	0.97	0.98	0.97	1.11
1061	Lubhu	0.86	1.03	1.33	1.42	1.30	1.05	0.74	0.78	0.73	0.85	0.85	0.85	0.98
1071	Buddha[4]	0.87	1.04	1.34	1.43	1.31	1.06	0.75	0.79	0.74	0.86	0.86	0.86	0.99
1073	Khokana	0.74	0.90	1.19	1.30	1.19	0.91	0.62	0.64	0.61	0.72	0.71	0.71	0.85
1074	Sundarijal	1.04	1.20	1.52	1.59	1.47	1.25	0.92	0.98	0.91	1.02	1.03	1.03	1.16
1075	Lele	1.17	1.34	1.67	1.72	1.59	1.41	1.07	1.14	1.05	1.16	1.17	1.16	1.30
KV	**Average**	**1.02**	**1.21**	**1.52**	**1.58**	**1.47**	**1.22**	**0.91**	**0.94**	**0.89**	**0.98**	**0.98**	**0.98**	**1.14**

([1]Bagbani, [2]Kathmandu Airport, [3]Changunarayan, [4]Buddhanilkantha)

(Source: Computed from Eq.12)

6.2.5 Atmospheric Parameters

Slope Vapor Pressure Curve (Δ)

Slopes of the vapour pressure curve at the mean monthly temperature values have been computed using Equation 4 and Equation 15 and presented in Table 17.

Psychrometric Constant (γ)

Psychrometric constant (γ) has been computed using Equation 16. The required atmospheric pressure data have been computed from Equation 18 and Latent Heat of Vaporization(λ) has been taken as 2.45 MJ kg^{-1} using Equation 17.

Table 17 : Slope of vapour pressure curve(Δ) at mean monthly temperature for 17 stations

St. Index	Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1007	Kakani	0.070	0.076	0.096	0.116	0.128	0.139	0.139	0.139	0.137	0.118	0.098	0.079
1015	Thankot	0.076	0.084	0.106	0.127	0.145	0.158	0.159	0.158	0.152	0.130	0.104	0.083
1021	Kirtipur	0.080	0.090	0.111	0.132	0.151	0.164	0.166	0.165	0.156	0.134	0.108	0.087
1022	Godawari	0.079	0.089	0.110	0.132	0.150	0.161	0.163	0.161	0.150	0.130	0.104	0.084
1029	Khumal	0.081	0.091	0.113	0.136	0.160	0.177	0.179	0.177	0.168	0.142	0.113	0.089
1030	Ktm airport	0.081	0.092	0.112	0.132	0.149	0.161	0.163	0.162	0.155	0.133	0.108	0.088
1035	Sankhu	0.078	0.088	0.108	0.128	0.141	0.150	0.152	0.152	0.144	0.124	0.103	0.085
1039	Panipokhari	0.077	0.088	0.109	0.129	0.145	0.155	0.158	0.158	0.151	0.130	0.105	0.085
1043	Nagarkot	0.069	0.075	0.094	0.113	0.119	0.125	0.126	0.125	0.121	0.108	0.090	0.075
1052	Bhakatapur	0.080	0.091	0.111	0.132	0.147	0.157	0.159	0.158	0.148	0.128	0.105	0.086
1059	Changunarayan	0.077	0.086	0.106	0.126	0.139	0.148	0.150	0.149	0.142	0.123	0.102	0.083
1060	Chapagaun	0.079	0.089	0.109	0.130	0.145	0.155	0.157	0.155	0.145	0.127	0.103	0.084
1061	Lubhu	0.080	0.091	0.111	0.132	0.148	0.158	0.160	0.159	0.149	0.129	0.105	0.085
1071	Buddhanilkatha	0.080	0.090	0.110	0.132	0.149	0.161	0.163	0.163	0.154	0.131	0.109	0.088
1073	Khokana	0.082	0.093	0.114	0.136	0.157	0.170	0.172	0.171	0.160	0.137	0.110	0.088
1074	Sundarijal	0.078	0.087	0.107	0.127	0.142	0.153	0.154	0.155	0.148	0.127	0.105	0.085
1075	Lele	0.077	0.086	0.106	0.127	0.141	0.150	0.151	0.150	0.141	0.123	0.100	0.082

(Source: Computed from Eq.4 and 15)

Table 18 : Atmospheric Pressure and Psychrometric constant of the different stations

St. Index	Location	Atm. Pressure in kPa	γ in kPa °C^{-1}
1007	Kakani	79.1663	0.0526
1015	Thankot	83.4593	0.0555
1021	Kirtipur (bagbani)	86.1822	0.0573
1022	Godawari	85.8096	0.0571
1029	Khumal	86.3275	0.0574
1030	Kathmandu airport	86.4730	0.0575
1035	Sankhu	85.3044	0.0567
1039	Panipokhari	86.4834	0.0575
1043	Nagarkot	78.2126	0.0520
1052	Bhakatapur	86.5354	0.0575
1059	Changunarayan	84.3421	0.0561
1060	Chapagaun	85.3147	0.0567
1061	Lubhu	86.4210	0.0575
1071	Buddha	86.3275	0.0574
1073	Khokana	87.7703	0.0584
1074	Sundarijal	84.8836	0.0557
1075	Lele	83.8642	0.0558

(Source: Computed from Eq.16 - 18)

6.2.6 Reference Evapotranspiration (ETo)

Considering the FAO-56 application of the Penman-Monteith (P-M) equation gives the best estimates of Reference Evapotranspiration (Nayava, 2005), Reference Evapotranspiration values of seventeen different stations of Kathmandu valley have been estimated using Equation 14. The Monthly Reference Evapotranspiration values in mm/day at seventeen different stations of Kathmandu valley have been presented in Table 19.

Table 19 : Monthly Reference Evapotranspiration (ETo) in mm/day

Stn. Index	Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual total
1007	Kakani	1.39	1.98	2.82	3.44	3.30	3.04	3.37	3.23	2.29	2.04	1.49	1.20	2.47
1015	Thankot	1.46	2.07	2.96	3.54	3.46	3.07	3.03	2.74	2.36	2.20	1.68	1.36	2.49
1021	Kirtipur[1]	1.37	2.01	2.91	3.52	3.50	3.10	2.90	2.69	2.40	2.17	1.59	1.26	2.45
1022	Godawari	1.34	1.98	2.86	3.52	3.55	3.09	3.00	2.74	2.39	2.18	1.60	1.25	2.46
1029	Khumaltar	1.36	2.00	2.91	3.54	3.60	3.21	2.89	2.76	2.50	2.16	1.58	1.25	2.48
1030	K.A.[2]	1.35	1.99	2.89	3.53	3.52	3.12	2.87	2.69	2.44	2.15	1.56	1.24	2.45
1035	Sankhu	1.37	1.99	2.90	3.52	3.47	3.08	3.07	2.84	2.38	2.20	1.62	1.27	2.48
1039	Panipokhari	1.36	2.00	2.89	3.47	3.55	3.11	2.87	2.68	2.44	2.15	1.56	1.24	2.44
1043	Nagarkot	1.29	1.89	2.71	3.32	3.39	2.99	3.18	2.66	2.39	2.11	1.51	1.15	2.38
1052	Bhakatapur	1.34	1.99	2.89	3.52	3.49	3.12	2.88	2.69	2.47	2.18	1.58	1.24	2.45
1059	Changu[3]	1.38	1.99	2.88	3.52	3.47	3.13	2.91	2.71	2.45	2.20	1.62	1.28	2.46
1060	Chapagaun	1.38	2.02	2.91	3.55	3.60	3.17	2.89	2.71	2.47	2.21	1.64	1.29	2.49
1061	Lubhu	1.35	2.00	2.91	3.48	3.56	3.24	2.88	2.71	2.50	2.17	1.59	1.25	2.47
1071	Buddha[4]	1.34	1.97	2.88	3.50	3.41	3.05	2.98	2.75	2.36	2.12	1.53	1.22	2.43
1073	Khokana	1.32	1.98	2.90	3.53	3.56	3.15	2.87	2.70	2.42	2.14	1.54	1.21	2.44
1074	Sundarijal	1.37	1.99	2.87	3.48	3.34	3.08	3.44	3.09	2.35	2.16	1.59	1.26	2.50
1075	Lele	1.42	2.04	2.89	3.52	3.56	3.13	2.94	2.75	2.48	2.28	1.68	1.33	2.50
KV	**Average**	**1.37**	**1.99**	**2.88**	**3.50**	**3.49**	**3.11**	**3.00**	**2.77**	**2.42**	**2.17**	**1.59**	**1.25**	**2.46**

([1]Bagbani, [2]Kathmandu Airport, [3]Changunarayan, [4]Buddhanilkantha)

(Source: Computed from Eq.14)

Reference crop evapotranspiration values from direct (Laboratory Experiment) and indirect (Penman/Monteith equation) methods had been computed by Shrestha & Shakya, (2004). The reference crop water requirement (ETo) measured and ETo calculated by Penman-Monteith were reported to be 3.9 mm/day and 4.0 mm/day respectively in the month of June and 3.18mm/day and 3.22mm/day respectively for the month of July whereas, the estimated ETo values at Kirtipur, computed here in this study, are 3.26 mm/day in June and 3.03 mm/day in July. These values of Evapotranspiration for the months June and July corresponds well with each other. The ETo's obtained from both Penman-Monteith and laboratory experimental method were also closed together. In general, a good estimate has been observed, with some exception where the reference evapotranspiration rates based on the estimated data vary by maximum of 0.5 mm. This results in an error of 15 mm/month on that month. Altogether, over the period of one year, an average error of 7 mm/month can be estimated between ETo calculated on the basis of measured data and on the basis of estimated data.

These estimated values of ETo for the stations Kakani, Khumaltar and Kathmandu airport correspond well throughout the range with the values of ETo of these stations reported by Pokhrel (1998)[Table 20]. Nevertheless, the values computed here in this study are found to be lower compared to the values reported by Pokhrel (1998). The monthly mean evapotranspiration values of Kathmandu Airport computed for 1968-1980 as reported by DHM (Appendix 21) are also more than the values computed here. But, the Pan Evaporation data of the Kathmandu valley clearly indicate, in general, the calculated values in this study are plausible.

Table 20 : Reference Evapotranspiration of three stations

Msld	**Location**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1007	Kakani	2.0	2.8	3.9	4.5	4.3	3.2	2.8	2.6	2.4	2.4	2.0	1.9
1029	Khumaltar	1.9	2.8	3.9	4.8	5.2	4.4	4.2	4.3	3.5	3.1	2.4	1.8
1030	KTM Airport	2.0	2.9	4.2	5.3	5.5	4.9	4.1	4.3	3.7	3.3	2.4	1.8

(Source: Pokhrel, 1998)

CHAPTER SEVEN

7. RESULT & DISCUSSION

Results and discussion for the values of Radiation and Reference Evapotranspiration from the analysis have been discussed in this chapter.

7.1 RADIATION (R_S AND R_n)

The average Global Extraterrestrial Radiation (R_a) in mm / day noted from the standard climatic table and the average incoming Solar Radiation (R_s) in mm / day over the Kathmandu valley are summarized in Table 21.

Table 21 : Average Extraterrestrial radiation (R_a) and Incoming solar radiation (R_s)

Radiation in mm/day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
R_a	9.28	11.28	13.48	15.40	16.50	16.90	16.70	15.80	14.20	12.08	9.88	8.78	13.35
R_s	5.79	6.98	8.12	8.84	8.43	7.29	7.55	7.04	6.38	6.92	6.19	5.46	7.08
R_s / R_a	0.62	0.62	0.60	0.57	0.51	0.43	0.45	0.45	0.45	0.57	0.63	0.62	0.53

(Source: Pokhrel, 1998 and Table 9)

Average solar radiation at the top of the ground (R_s) is found to be around 7.08 mm/day (201 W/m^2 or 17.36 MJ/m^2/day). In Kathmandu valley, solar radiation data clearly showed the seasonal variation. R_s values are found to be ranging from 5.46 mm/day (154.88 W/m^2 or 13.38 MJ/m^2/day in December to 8.84 mm/day (250.77 W/m^2 or 21.66 MJ/m^2/day) in April. The higher values more than 8 mm/day (227 W/m^2 or 19.6 MJ/m^2/day) of solar radiation occurred during March to May.

R_s / R_a ratio shows that during monsoon season the solar radiation received above earth surface (R_s) is less than half of global extraterrestrial radiation (R_a), whereas, in winter months, it is more than 60 % of R_a. This is due to higher cloud cover during the monsoon months than in the winter months. The maximum R_s could be only upto 75 % of R_a.

The average Net shortwave radiation (R_{ns}), Net longwave radiation (R_{nl}) and Net radiation (R_n) in mm/day over Kathmandu valley have been summarized in Table 22. Average annual net radiation (R_n) was found to be around 2.91 mm/day (82.55 W/m^2 or 7.13 MJ/m^2/day). Seasonal variation of net radiation was observed in Kathmandu valley. R_n values are found to be ranging from 4.11 mm/day (116.59 W/m^2 or 10.07 MJ/m^2/day) in May to 1.22 mm/day (34.61 W/m^2 or 2.99 MJ/m^2/day) in December. The higher values more than 3 mm/day occurred during March to September.

Table 22 : Net shortwave radiation (R_{ns}), Net longwave radiation (R_{nl}) and Net radiation (R_n) in mm /day

Radiations in mm/day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
R_{ns}	4.46	5.38	6.25	6.81	6.49	5.61	5.82	5.42	4.92	5.33	4.77	4.20	5.45
R_{nl}	2.96	2.99	2.97	2.83	2.38	1.78	1.93	1.88	1.91	2.79	3.12	2.99	2.54
R_n	1.49	2.39	3.28	3.97	4.11	3.83	3.89	3.54	3.01	2.53	1.65	1.22	2.91

(Source: computed from Eq. 21, 23 and Table 14)

The annual distribution of all the radiation components in W/m^2 has been shown below in figure 12. The spatial patterns of distribution of R_s and R_n (in W/m2) for each month have been depicted through the monthly solar radiation maps (Figure 13 - 24) and in the Net radiation maps (Figure 25 - 36).

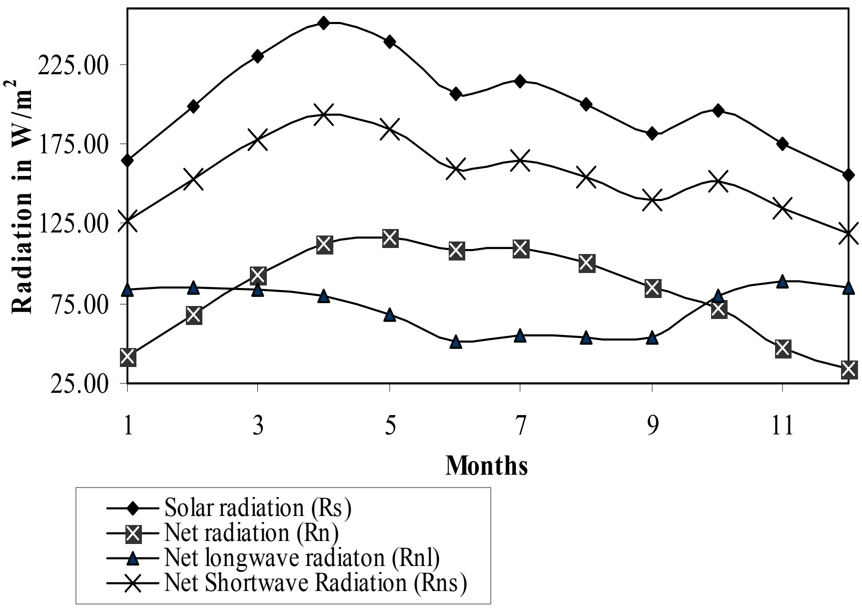


Figure 12 : Annual trend of Radiation in Kathmandu Valley

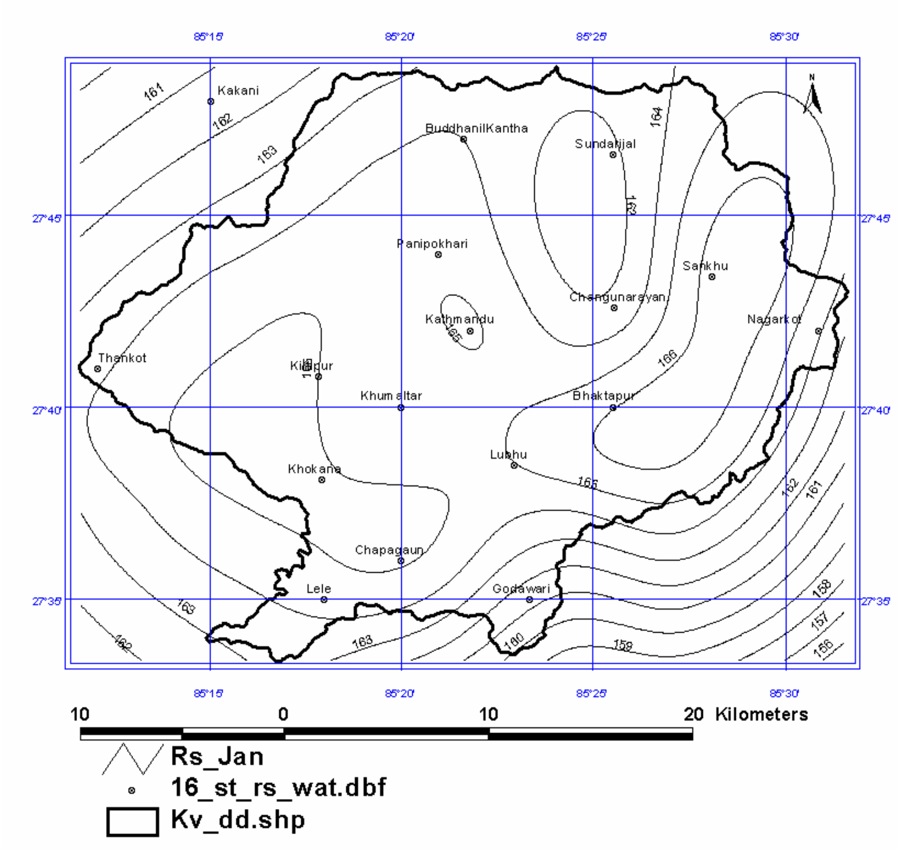


Figure 13 : Mean Solar radiation (W/m^2) in January

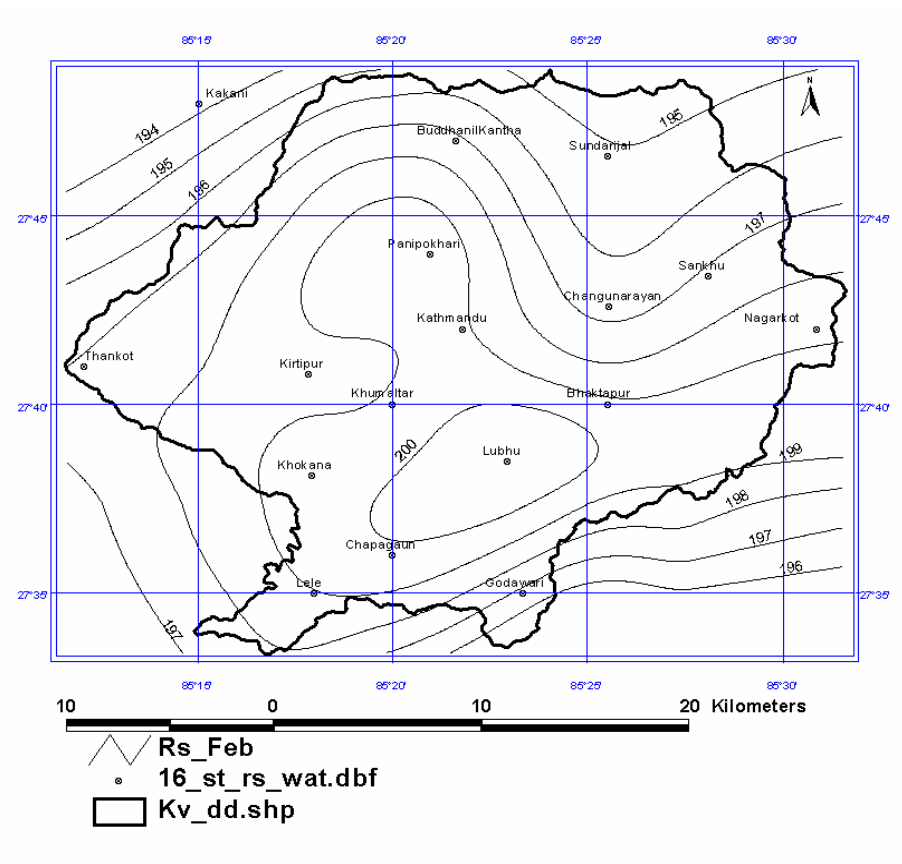


Figure 14 : Mean Solar radiation (W/m^2) in February

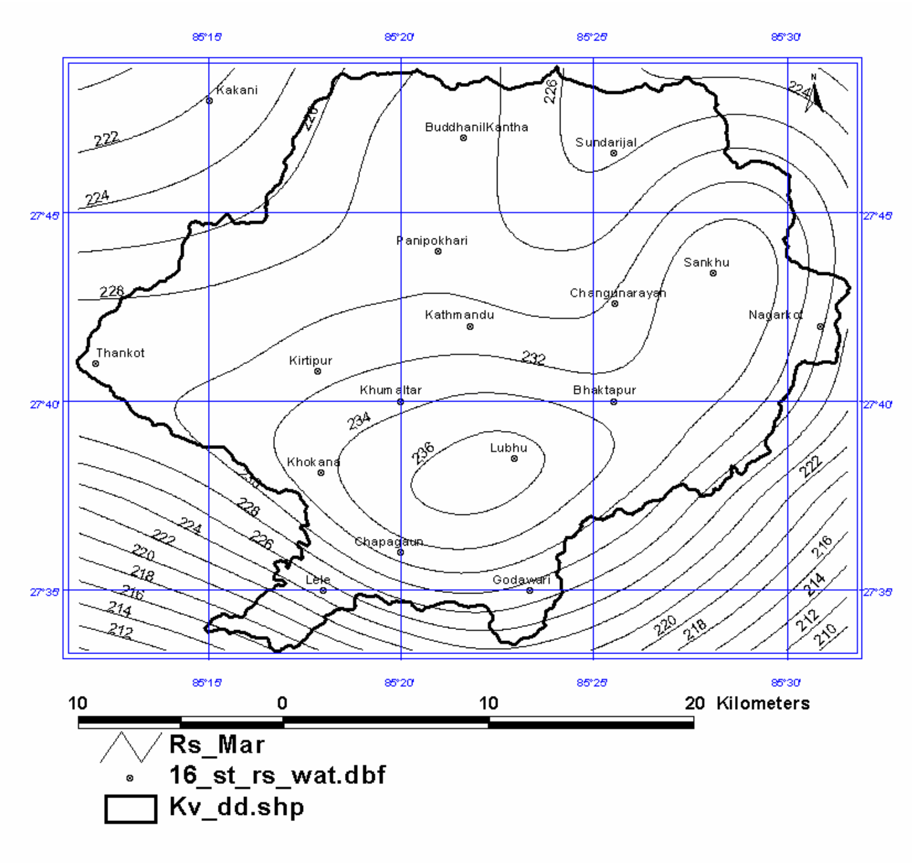


Figure 15 : Mean Solar radiation (W/m^2) in March

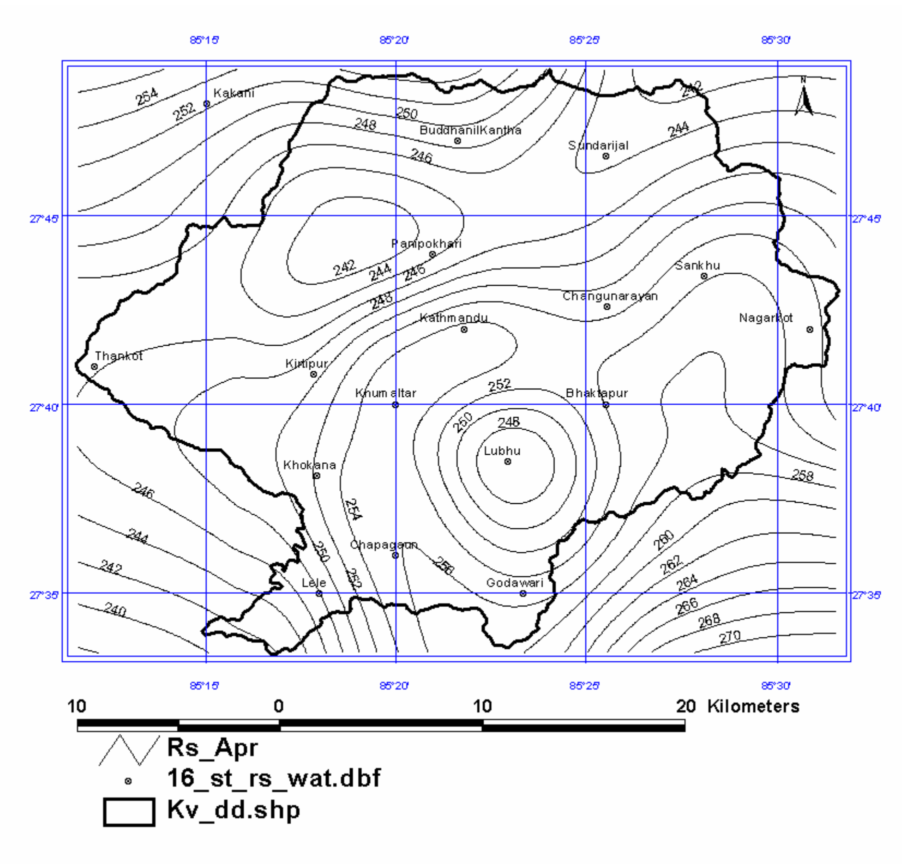


Figure 16 : Mean Solar radiation (W/m^2) in April

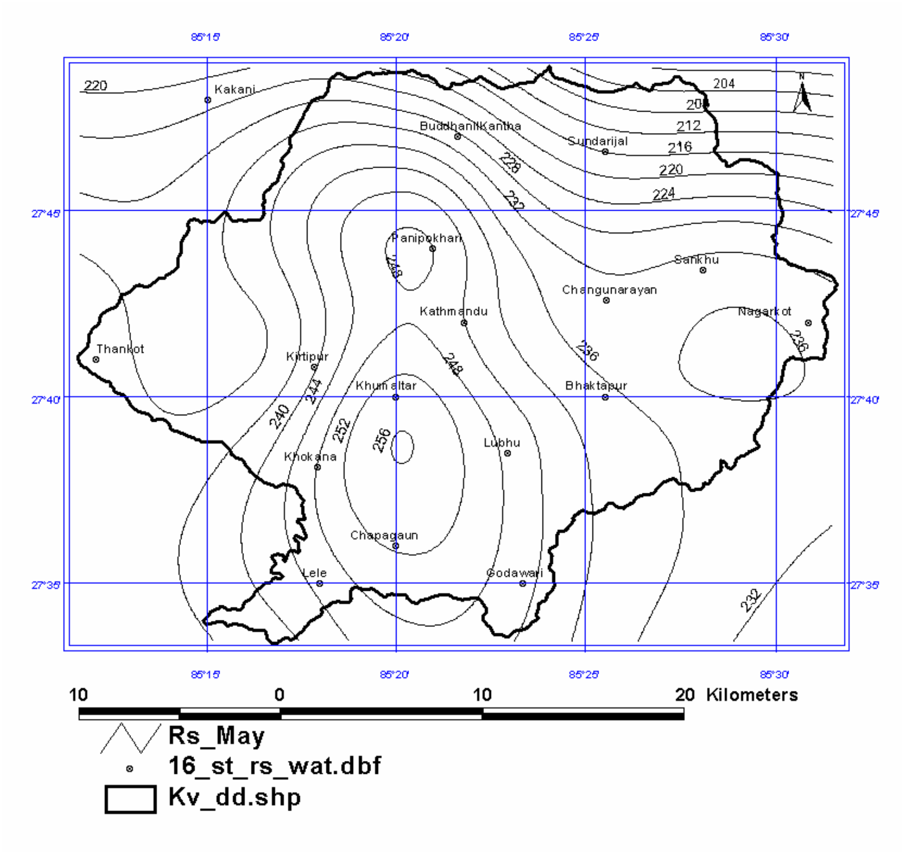


Figure 17 : Mean Solar radiation (W/m^2) in May

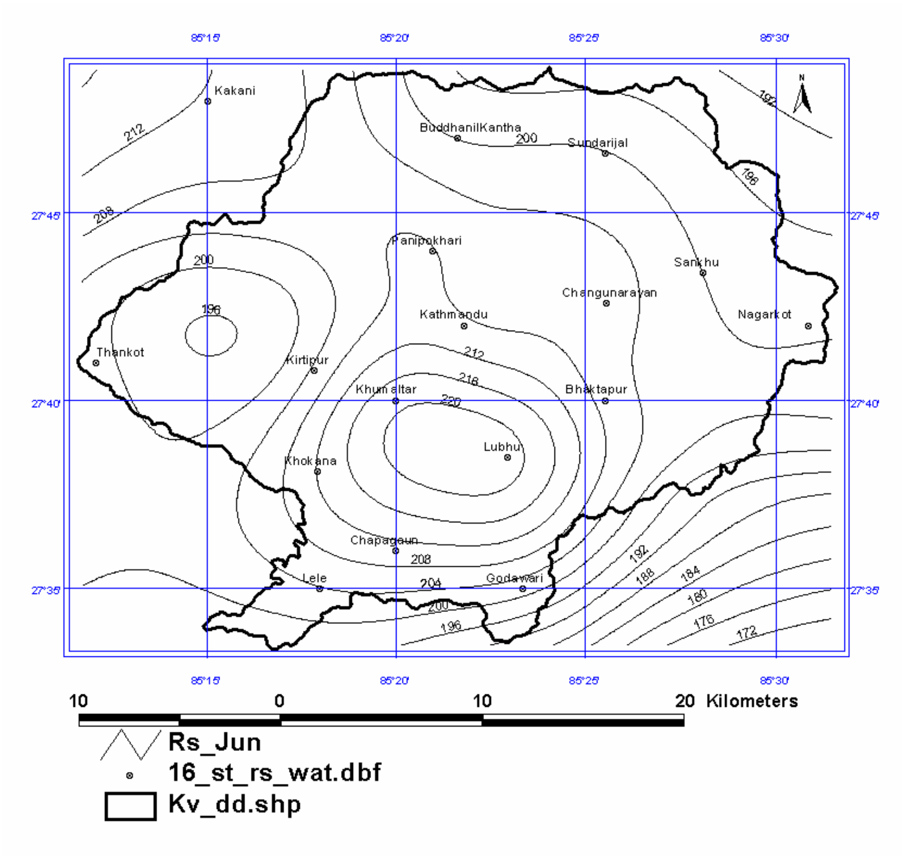


Figure 18 : Mean Solar radiation (W/m^2) in June

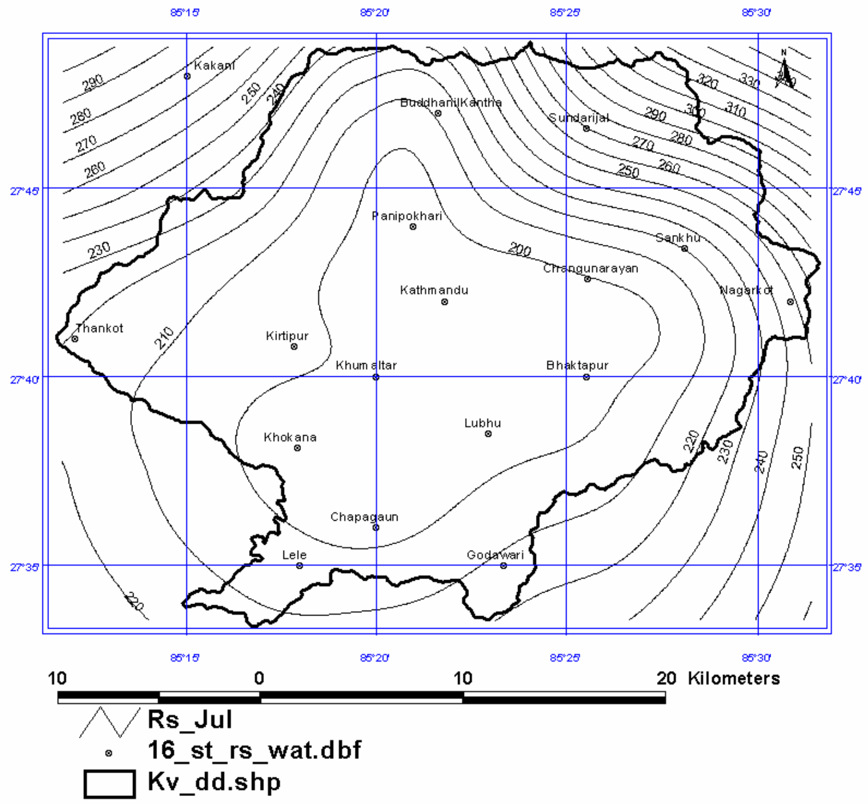


Figure 19 : Mean Solar radiation (W/m²) in July

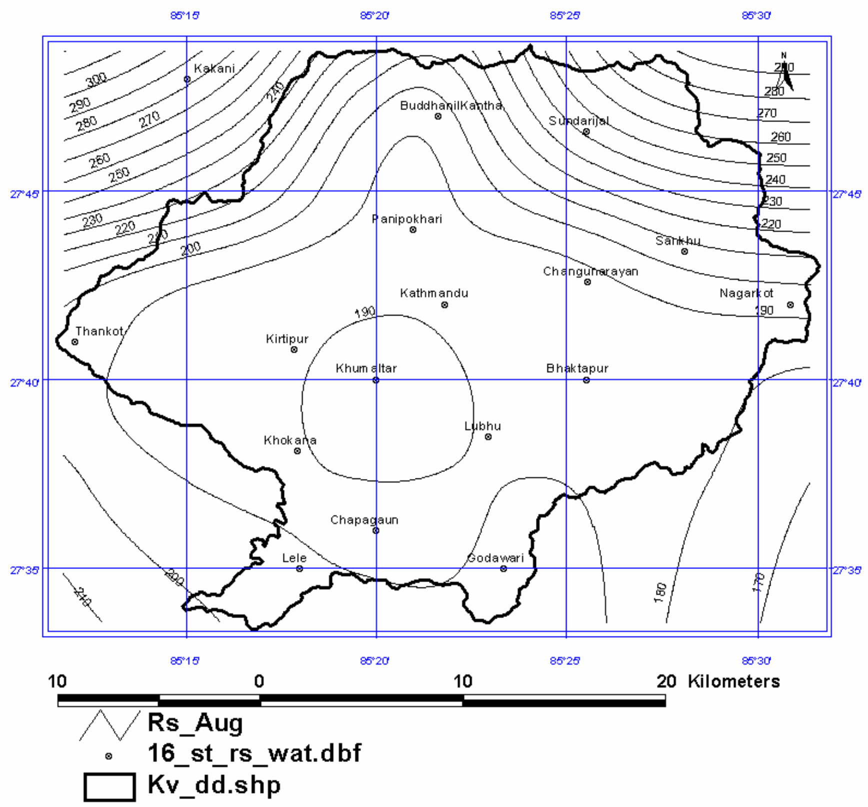


Figure 20 : Mean Solar radiation (W/m²) in August

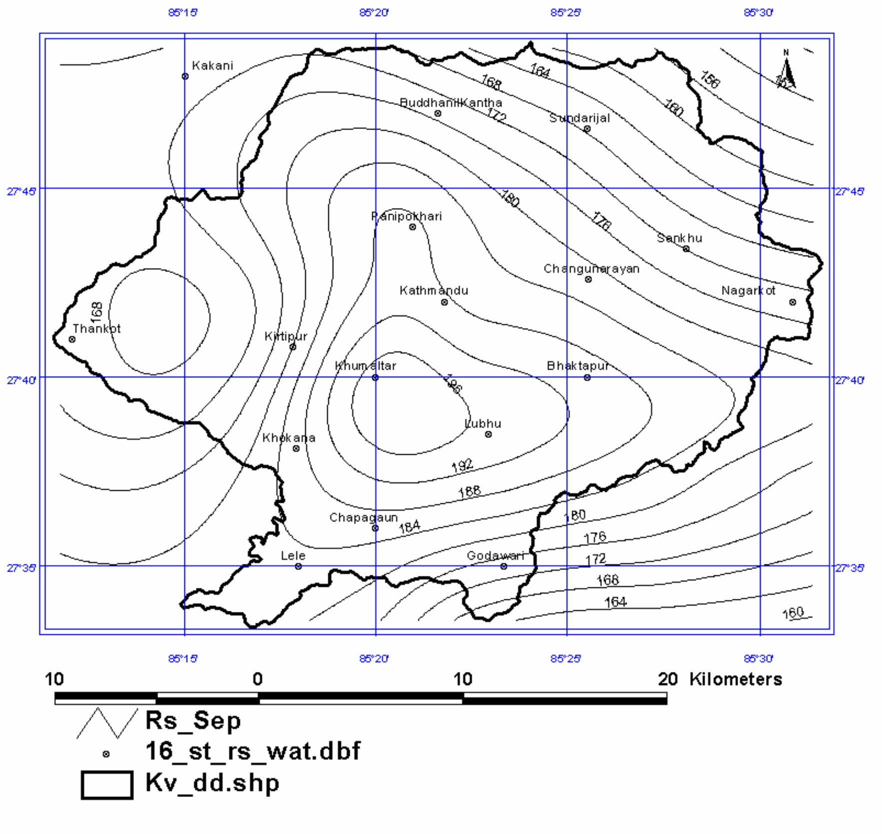


Figure 21 : Mean Solar radiation (W/m^2) in September

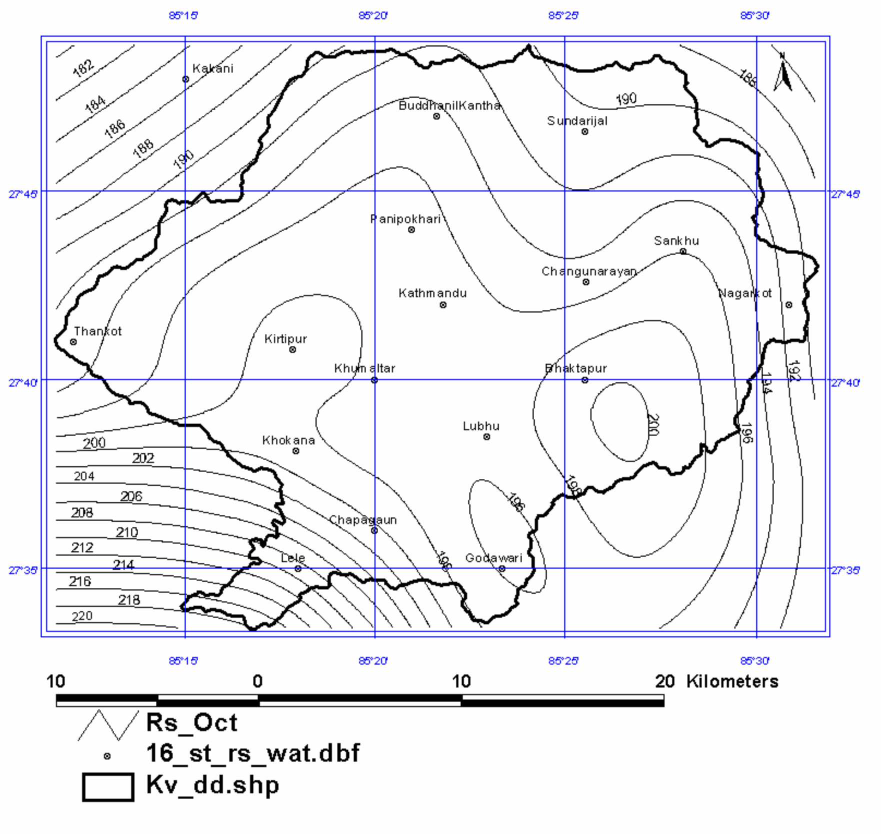


Figure 22 : Mean Solar radiation (W/m^2) in October

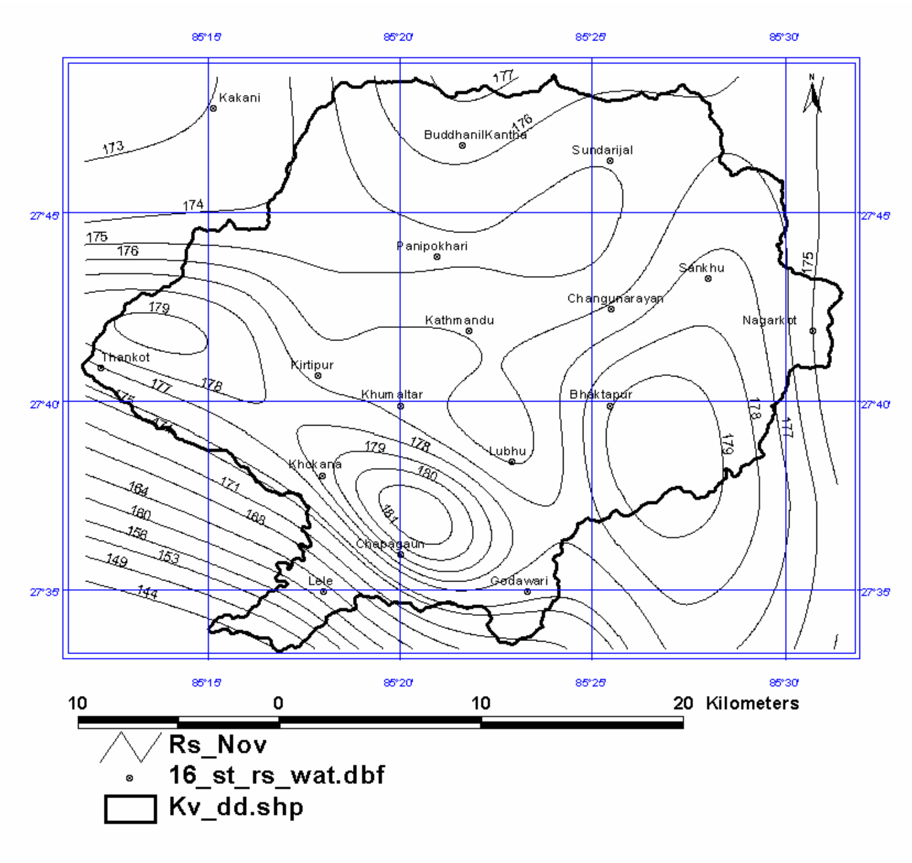


Figure 23 : Mean Solar radiation (W/m^2) in November

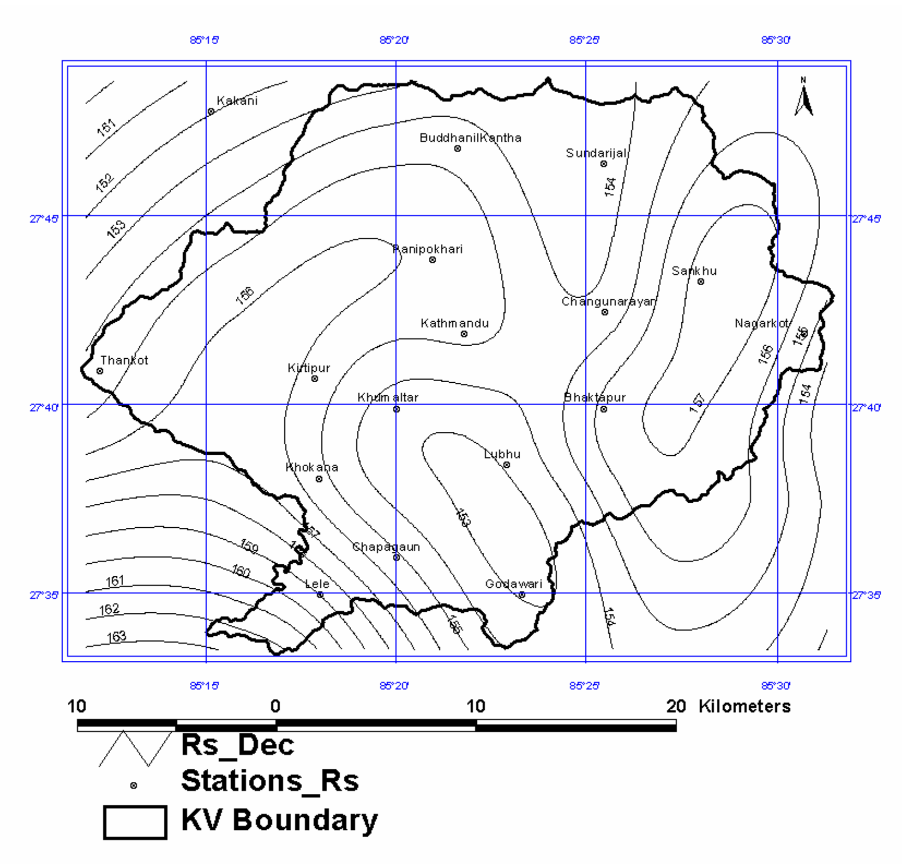


Figure 24 : Mean Solar radiation (W/m^2) in December

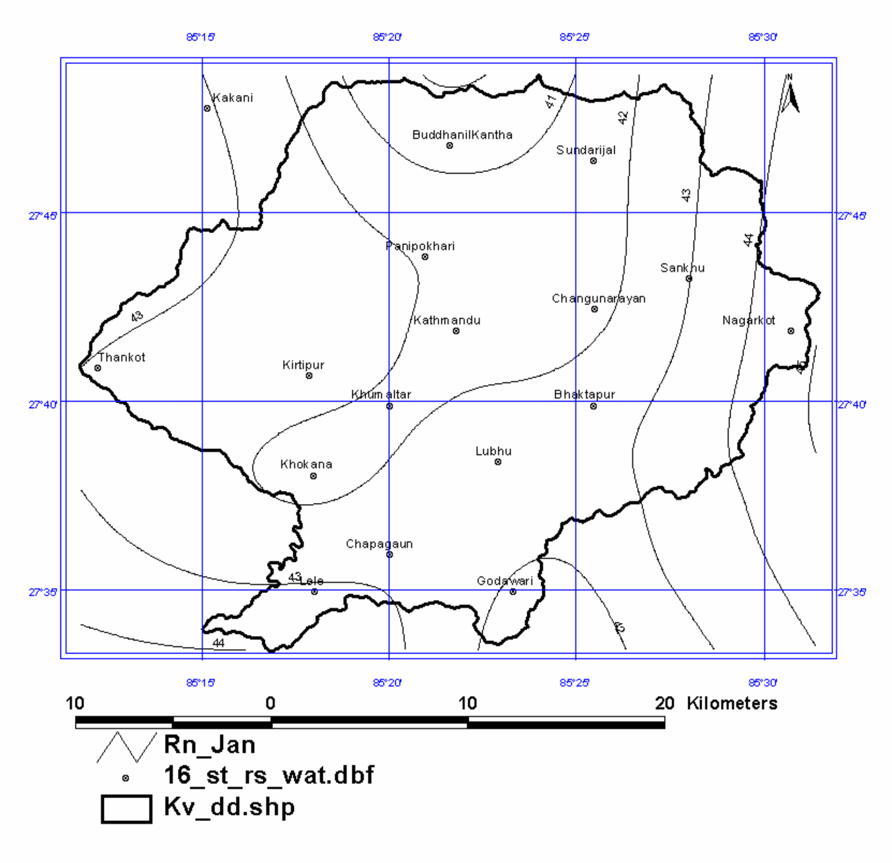


Figure 25 : Mean Net radiation (W/m^2) in January

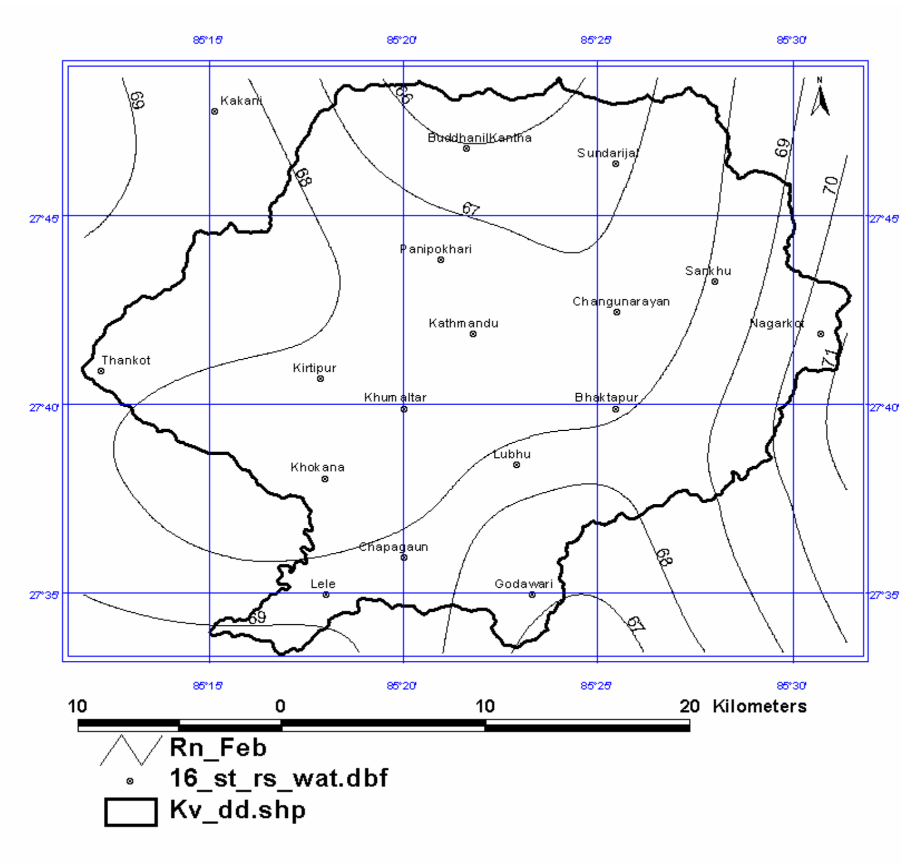


Figure 26 : Mean Net radiation (W/m^2) in February

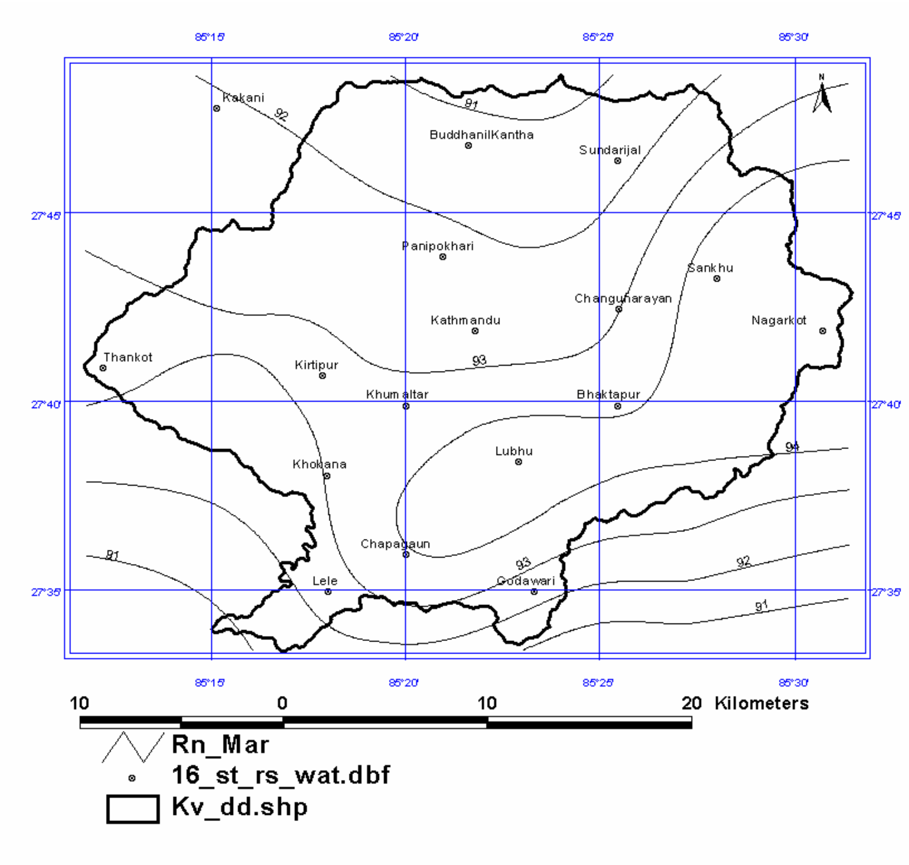


Figure 27 : Mean Net radiation (W/m^2) in March

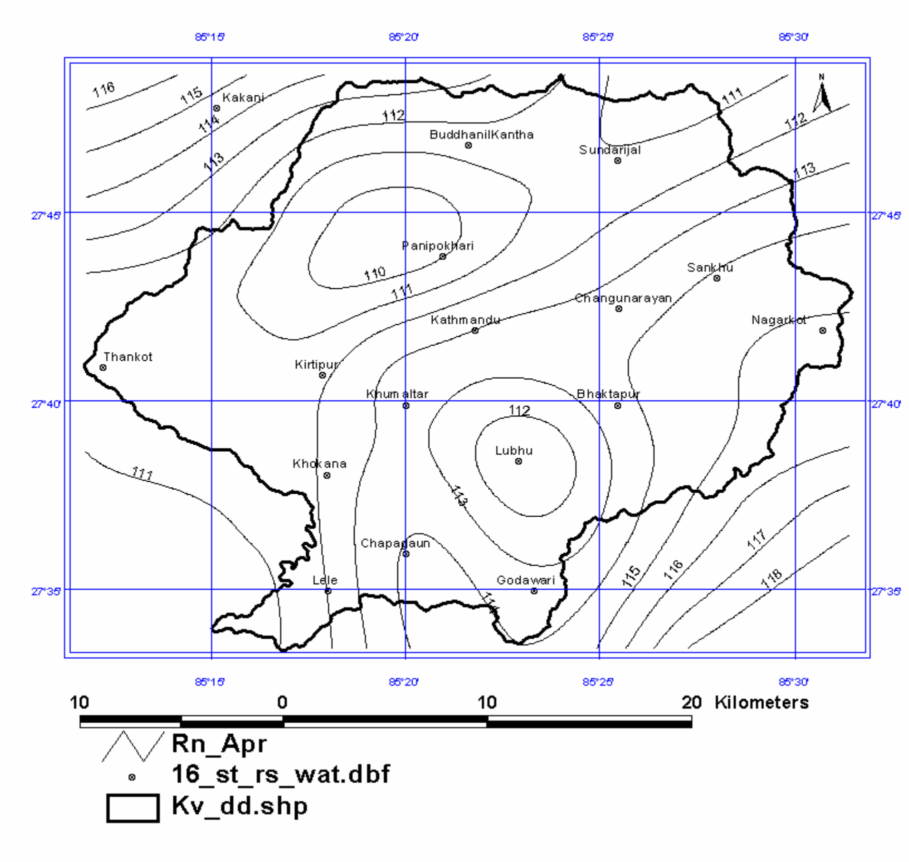


Figure 28 : Mean Net radiation (W/m^2) in April

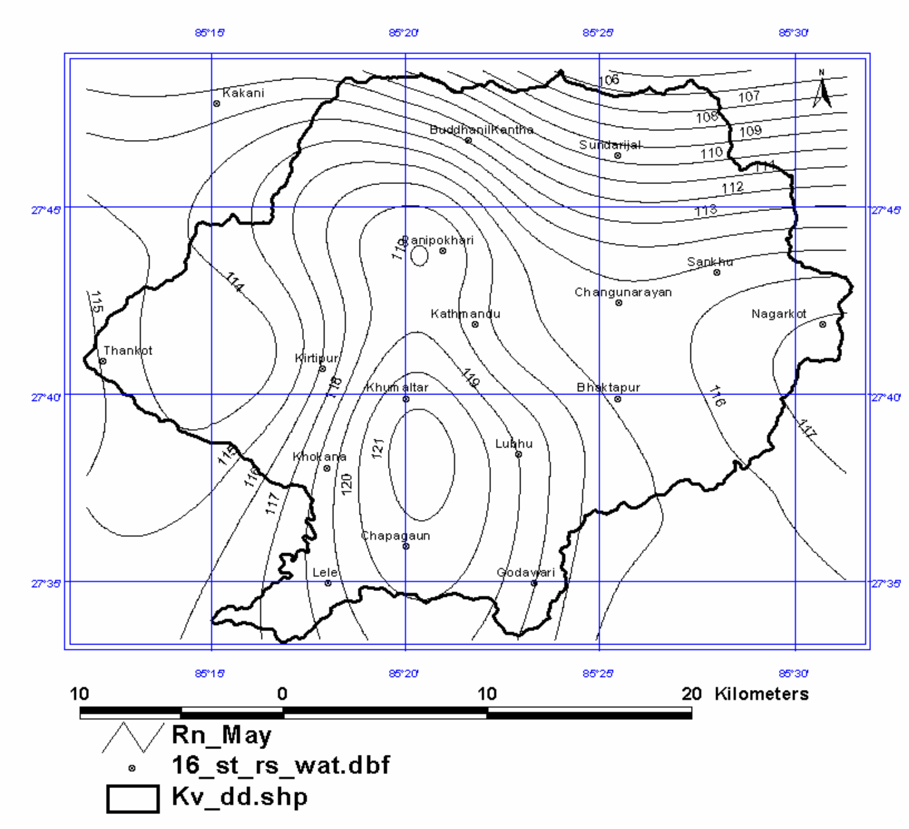


Figure 29 : Mean Net radiation (W/m^2) in May

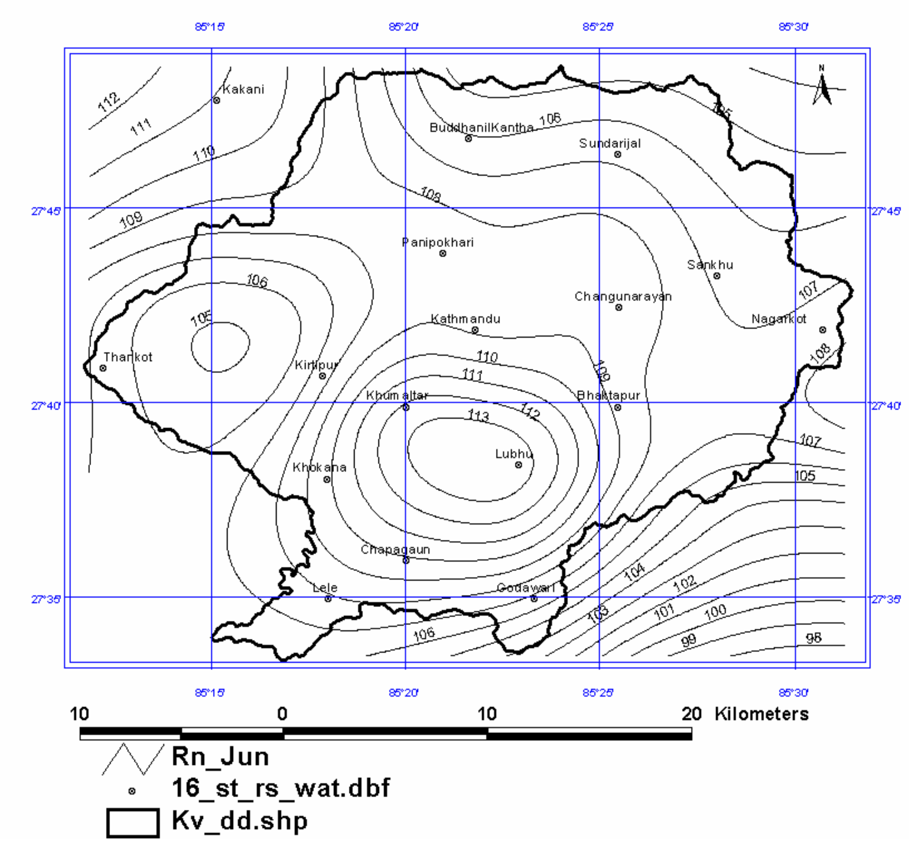


Figure 30 : Mean Net radiation (W/m^2) in June

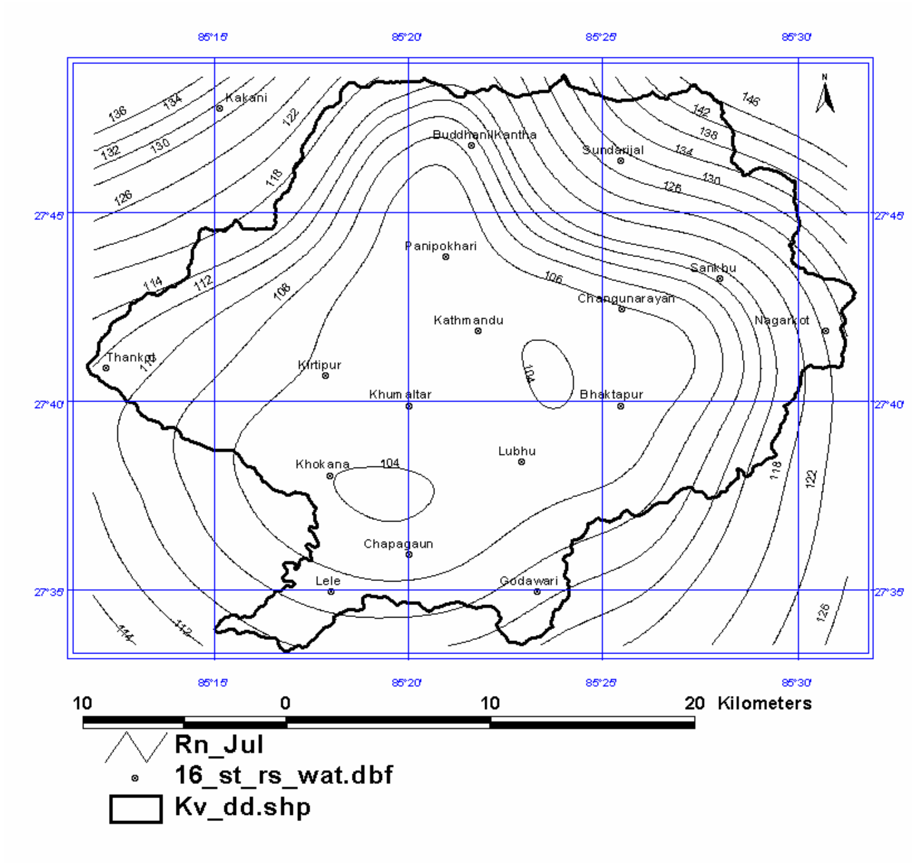


Figure 31 : Mean Net radiation (W/m^2) in July

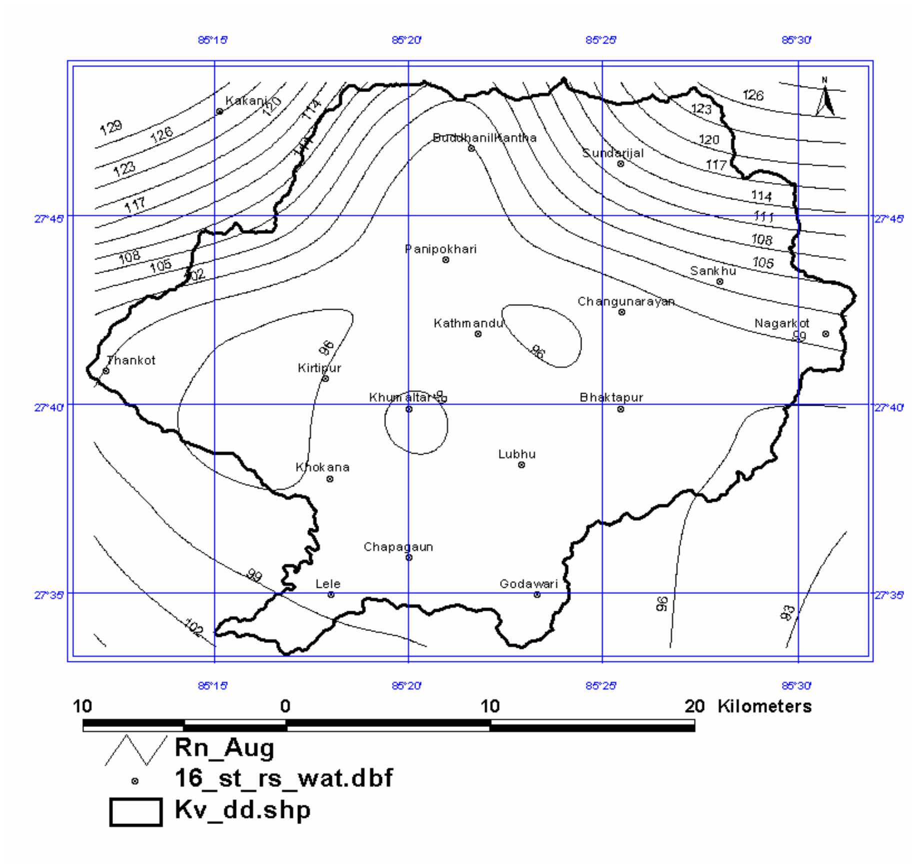


Figure 32 : Mean Net radiation (W/m^2) in August

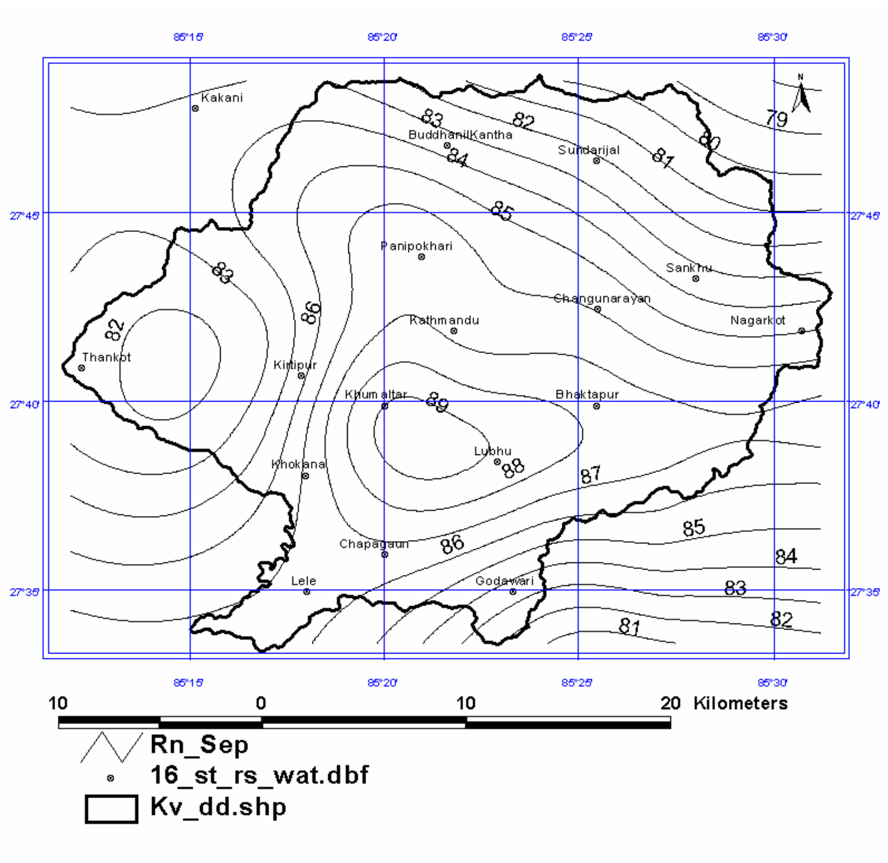


Figure 33 : Mean Net radiation (W/m^2) in September

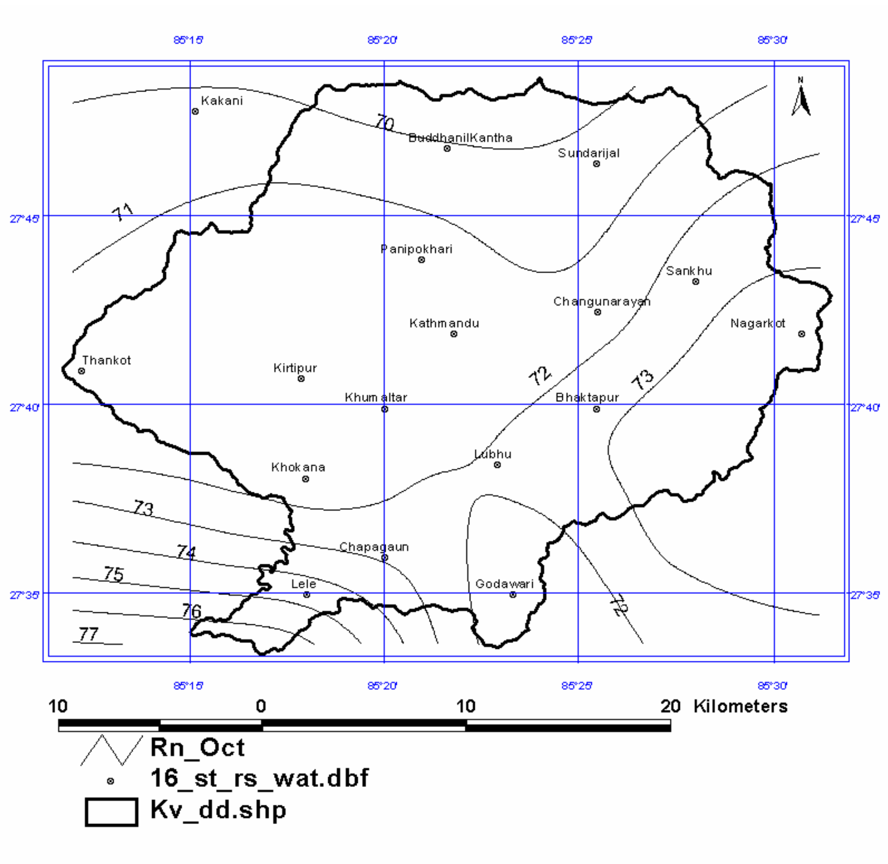


Figure 34 : Mean Net radiation (W/m^2) in October

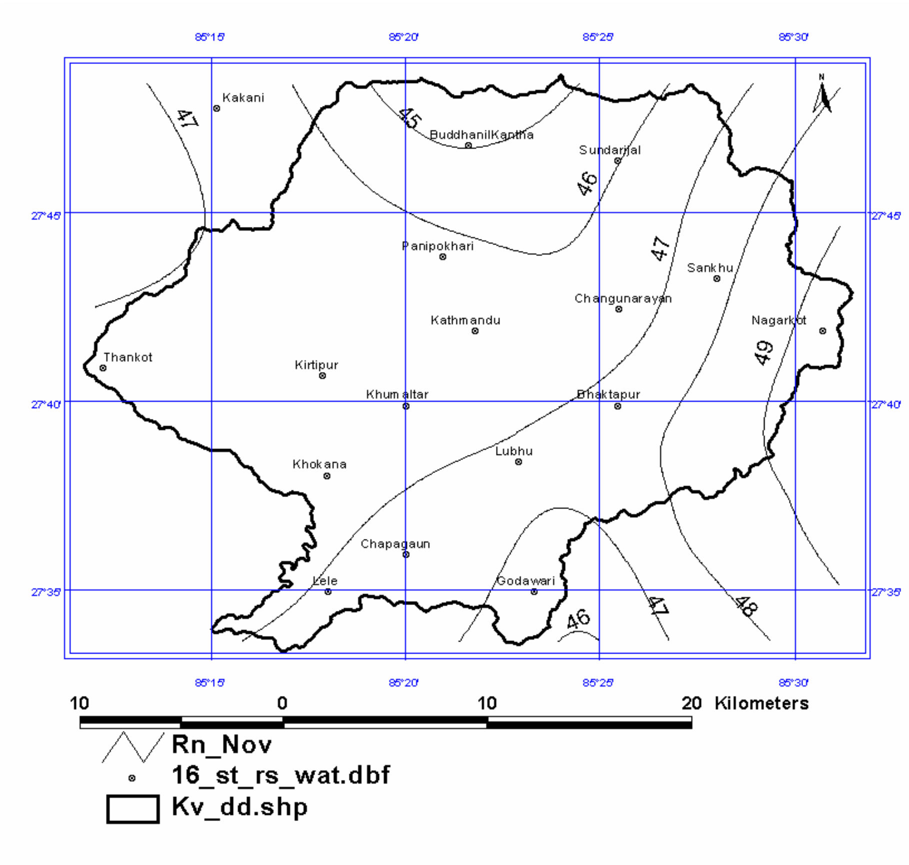


Figure 35 : Mean Net radiation (W/m^2) in November

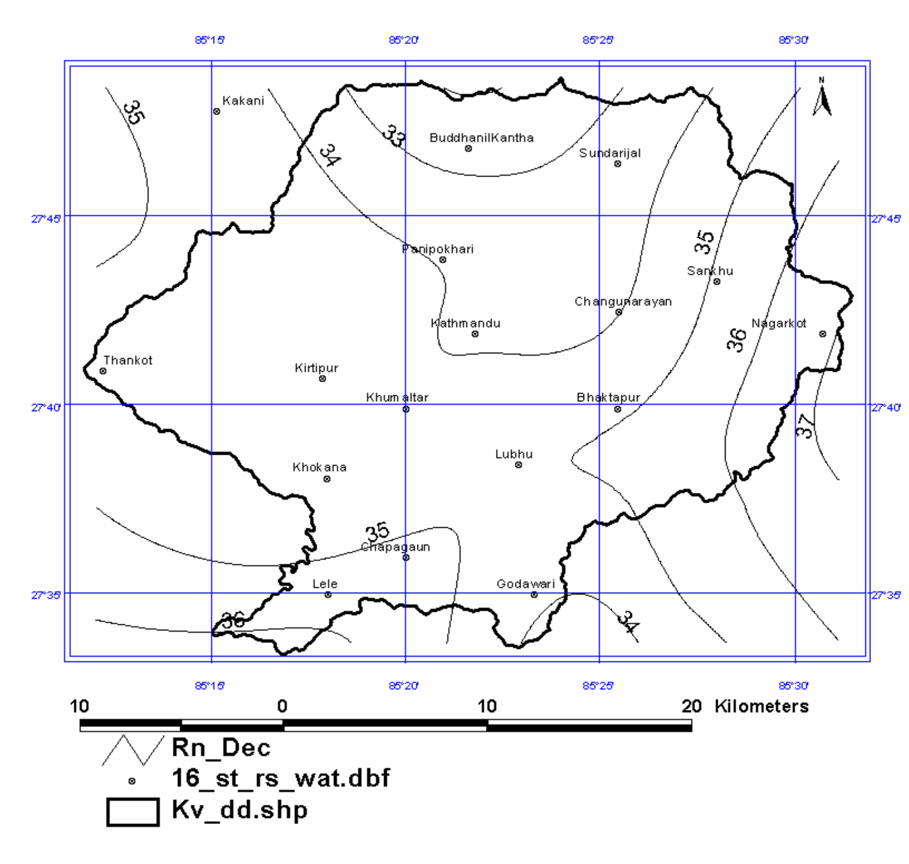


Figure 36 : Mean Net radiation (W/m^2) in December

7.2 Reference Evapotranspiration (ETo)

The average Reference Evapotranspiration and average Pan Evaporation over Kathmandu Valley has been summarize in Table 23. The Reference Evapotranspiration values in the Kathmandu valley range from 1.26 mm/day, in December, to about 3.62 mm/day in the month of April. The average daily ETo is estimated to be 2.5 mm/day in Kathmandu valley. The daily ETo and monthly ETo found to be highest just before the onset of monsoon during pre-monsoon season (April, May and June).

The ratio of PET / Pan Evaporation or ETo/E ratio gives the pan coefficient which is generally taken as 0.8. The calculated values of Pan coefficient for Kathmandu valley have been shown in Table 23 .The values is concentrated around 0.8, this signifies that estimated ETo values are fairly close to the real values and good estimation has been done.

Table 23 : Average estimated ETo, Pan Evaporation (E) in mm/ day and ETo / E

Parameters	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual mean
Average ETo	1.37	1.99	2.88	3.50	3.49	3.11	3.00	2.77	2.42	2.17	1.59	1.25	2.46
Average Pan Evaporation (E)	1.79	2.48	3.65	4.29	4.08	3.53	3.34	3.15	2.93	2.91	2.17	1.66	3.00
ETo/E	0.76	0.80	0.79	0.82	0.86	0.88	0.90	0.88	0.82	0.74	0.73	0.75	0.82

The average Experimental Evapotranspiration and measured Evaporation for the month of April, May, June and July at T. U., Kirtipur reported by Shakya and Shrestha (2004) had been listed in the Table 24. Total Pan Evaporation of 776 mm has been recorded for 6 month period (starting from April 2004) in the Kathmandu valley. The values of ETo estimated in this study are close to that reported by Shakya and Shrestha (2004). The Evaporation is found to be high during pre-monsoon season. The evaporation decreases as monsoon progresses. Thus, rainfall decreases the rate of evaporation since there is low solar radiation.

Table 24 : Experimental ETo and Pan Evaporation at T. U. / Kirtipur

Parameters	Apr	May	Jun	Jul
Experimental ETo, mm/day	3.35	3.96	3.9	3.18
Pan evaporation, E, mm/day	4.29	4.74	4.8	3.36
ETo/E	0.78	0.83	0.81	0.94

(Source: Shakya and Shrestha, 2004)

7.2.1 Water Budget

The mean daily ETo values were sum up for a month to get the total monthly ETo for every months. The total monthly ETo and total monthly rainfall over Kathmandu valley have been presented in Table 25. These monthly ETo and monthly rainfall values shows the simplified overview of hydrological water budget of Kathmandu Valley.

Table 25 : Monthly ETo, Monthly Rainfall and Water surplus of Kathmandu valley

Parameters	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual total (mm)
ETo (mm/month)	41.10	59.70	86.40	105.00	104.70	93.30	90.00	83.10	72.60	65.10	47.70	37.50	886.20
Monthly rainfall P (mm/month)	15.17	20.27	33.47	62.78	134.58	298.95	460.23	423.01	240.13	61.92	12.29	16.68	1779.49
Surplus (P – ETo) in mm	-25.93	-39.43	-52.93	-42.22	29.88	205.65	370.23	339.91	167.53	-3.18	-35.41	-20.82	893.29

(Source: computed from Table 23 & Appendix 2)

Annual total ETo is estimated to be 886.20 mm and the annual rainfall surplus for the Kathmandu valley is 893.29 mm or 0.893 m. The area of upper Bagmati catchment is 583 square km. The measured and published mean discharge of Bagmati River is 15.6 m^3/s (at Khokana). Changing volumes into depth the measured discharge is equivalent to 0.8409 m or 840 mm which approaches to estimated water surplus value of Kathmandu Valley. The error is found to be around 6.38 %. Thus, mean river runoff at the outlet of Kathmandu valley watershed and annual rainfall surplus calculated from the estimated ETo are fairly close.

The result showed higher annual rainfall in Kathmandu valley and only half of annual rainfall lost as evapotranspiration in Kathmandu Valley. In dry season, soil moisture is available for farming but a little water need to be added through the irrigation system.

The Annual trend of Reference Evapotranspiration along with that of annual rainfall is depicted in the Figure 37. The maximum monthly ETo of 108.74 mm is estimated to occurred in the month of April. The long term monthly distribution of potential evapotranspiration calculated on the basis of Pan Evaporation in Jiri also peak in April. (Merz, 2004). This distribution is important in terms of agricultural water demands. During this time, maize is broadcasted on the rainfed agricultural land and rice seedbed is prepared.

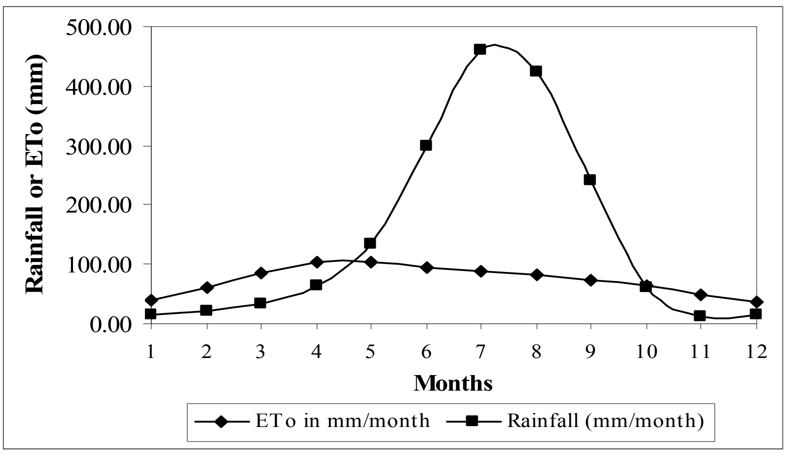


Figure 37 : Annual distribution of monthly Rainfall and monthly ETo in mm / month

The estimated annual ETo for the climate station in western Nepal ranges from 1168 mm/y at Daman to 1304 mm/y at Rampur (TAHAL Consulting, 2002 as cited in Merz 2004). Here, in this study the annual ETo is only 886 mm; so, significant difference has been observed in comparison to values reported by TAHAL Consulting Engineers (2002). But, the values of TAHAL Consulting Engineers (2002) are from Western Nepal. A considerable difference in terms of sunshine hours between the western and the central parts of the country have been observed.

The PET of Kathmandu airport and Godawari stations using Thronthwaite method (Gongal, 2003) are presented in Table 26. The ETo values computed in this study are higher in dry seasons and lower in wet seasons in comparison to values reported by Gongal, 2003. It has to be noted that the given values of Gongal (2003) are calculated using Thronthwaite method and its applicability should be checked first which is beyond the objective of the study.

Table 26 : PET in mm/month of Kathmandu Airport & Godawari (Calculated from Thronthwaite method)

PET (adjust) at	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual total (mm)
Ktm Airport	17.20	26.16	48.87	76.12	118.4	123.73	124.8	123.23	96.64	70.16	41.26	21.17	887.77
Godawari	17.20	17.94	27.08	51.50	76.94	105.91	109.68	107.15	104.91	82.60	63.84	40.35	805.1

(Source: Gongal, 2003)

7.2.2 Surface Energy Budget

The Estimated ETo and Net radiation are the components of daily surface energy budget. The general overview of surface energy budget is presented here. The energy arriving at the surface must equal the energy leaving the surface for the same time period. The surface energy balance equation for an evaporating surface can be written as:

$$R_n - G - \lambda E - H = 0$$

where R_n is the net radiation, H the sensible heat, G the subsurface transport or soil heat flux and λE the latent heat flux ≈ ETo. All the terms must have same unit. Positive R_n supplies energy to the surface and positive G, ETo and H remove energy from the surface. G beneath the reference grass surface is relatively small and equals to zero; it may be ignored for 24-hour time steps. Therefore,

$$H = R_n - \lambda E$$

All the components of daily and annual surface energy budget of Kathmandu valley have been presented in Table 27 and annual trend is depicted in Figure 38.

Table 27 : Average daily surface energy budget of Kathmandu valley in each month

Energy fluxes in MJ $m^{-2}day^{-1}$	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Net Radiation (R_n)	3.65	5.86	8.04	9.73	10.07	9.39	9.53	8.68	7.38	6.20	4.04	2.99
Latent Heat Flux (λE)	3.36	4.88	7.06	8.58	8.55	7.62	7.35	6.79	5.93	5.32	3.90	3.06
Surplus [Sensible Heat Flux (H)]	0.29	0.98	0.98	1.15	1.52	1.76	2.18	1.89	1.45	0.88	0.15	-0.07
Storage [Subsurface transport (G)]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

The annual total Net radiation and Latent heat flux are found to be 2603.31 MJ m^{-2} and 2200.74 MJ m^{-2}. The annual total surplus energy is 402.5 MJ m^{-2}. This surplus energy is distributed as sensible and Soil heat flux.

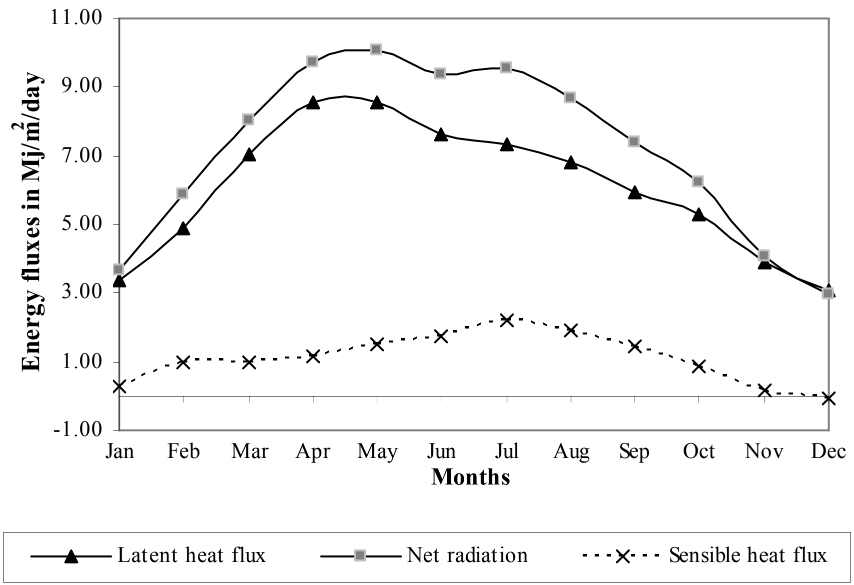


Figure 38 : Annual trend of Daily surface energy balance at Kathmandu Valley

7.3 ETo Maps (Spatial Distribution)

Depending on the spatial distribution of the different parameters related for ETo computation, ETo varies according to the elevation, surface steepness (slope) and surface orientation (aspect) [Shilpakar, 2003]. The flat valley and the steep surface oriented towards sun direction have higher ETo whereas the steep slopes oriented opposite to sun direction have low ETo. It has been seen that the ETo varies significantly by orientation. The spatial pattern of annual total ETo distribution over seventeen different stations in Kathmandu valley are depicted in figure 39.

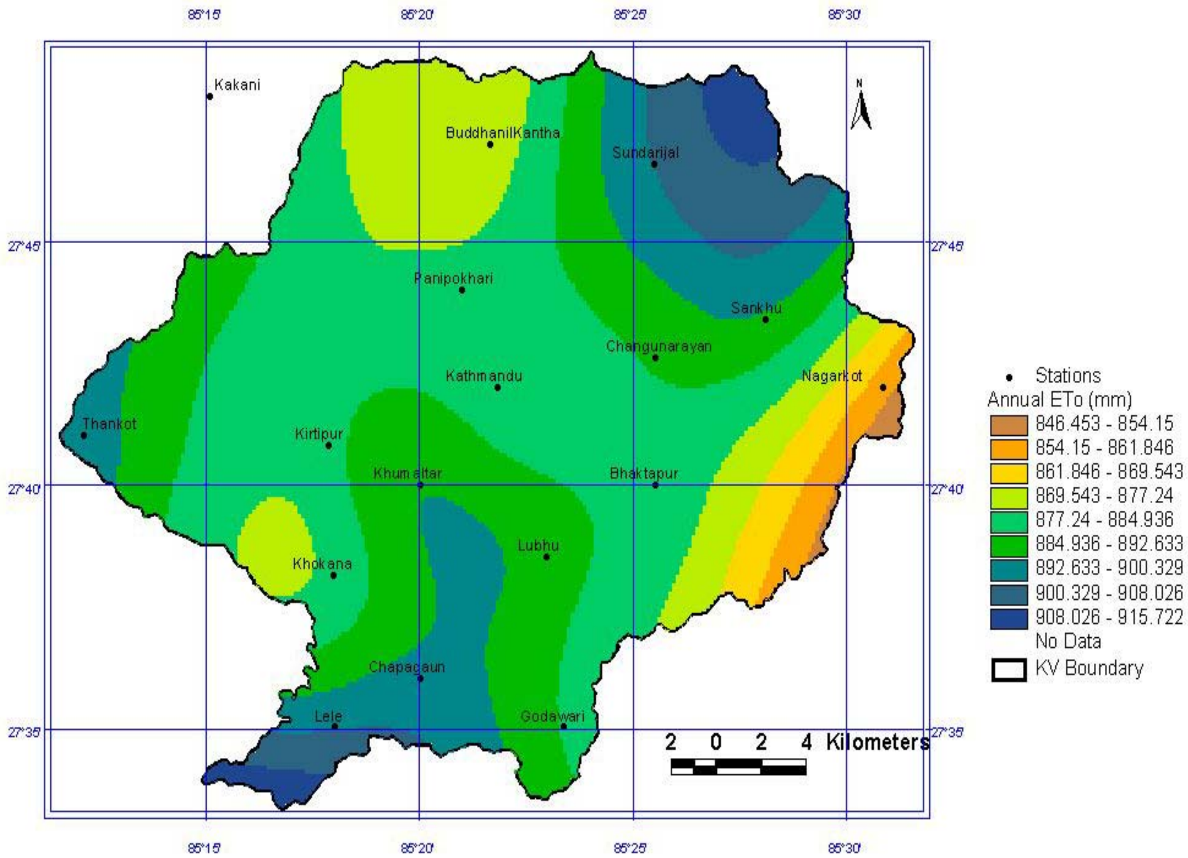


Figure 39: Spatial pattern of the total annual ETo (mm) distribution within the Kathmandu Valley.

Figure 39 indicates that the highest reference evapotranspiration rates have been expected in the southern aspect of northern hills of Kathmandu valley facing towards the sun whereas the northern aspect of south-eastern hills opposite to sun direction experience comparatively lower ETo in general. Locations such as Godawari, Nagarkot at the south-eastern part of valley have comparatively lower annual ETo or PET whereas the locations such as Thankot, Sundarijal have comparatively higher annual ETo with some exceptions. Due to variation in solar radiation resulting from surface steepness and orientation, the higher variations in ETo in the mountain environment have been observed here. Hence, for accurate estimation of the evapotranspiration in the slopping terrain likewise in context of Nepal, mountain radiation model is necessary.

Pokhrel (1998) and Merz (2004) reported that ETo decreases with altitude. Here, the annual ETo has been found to be comparatively higher at Khokana and lower at Nagarkot, the lowest and highest elevation stations respectively among the considered. However, some exception with higher ETo at higher elevation stations have also been observed; this may be due to higher wind speed and south aspect of the locations and also due to error in input data estimations. The spatial patterns of Reference Evapotranspiration distribution over the Kathmandu valley for each month of year have been depicted in the gridded ETo maps (Figure 40 - 51).

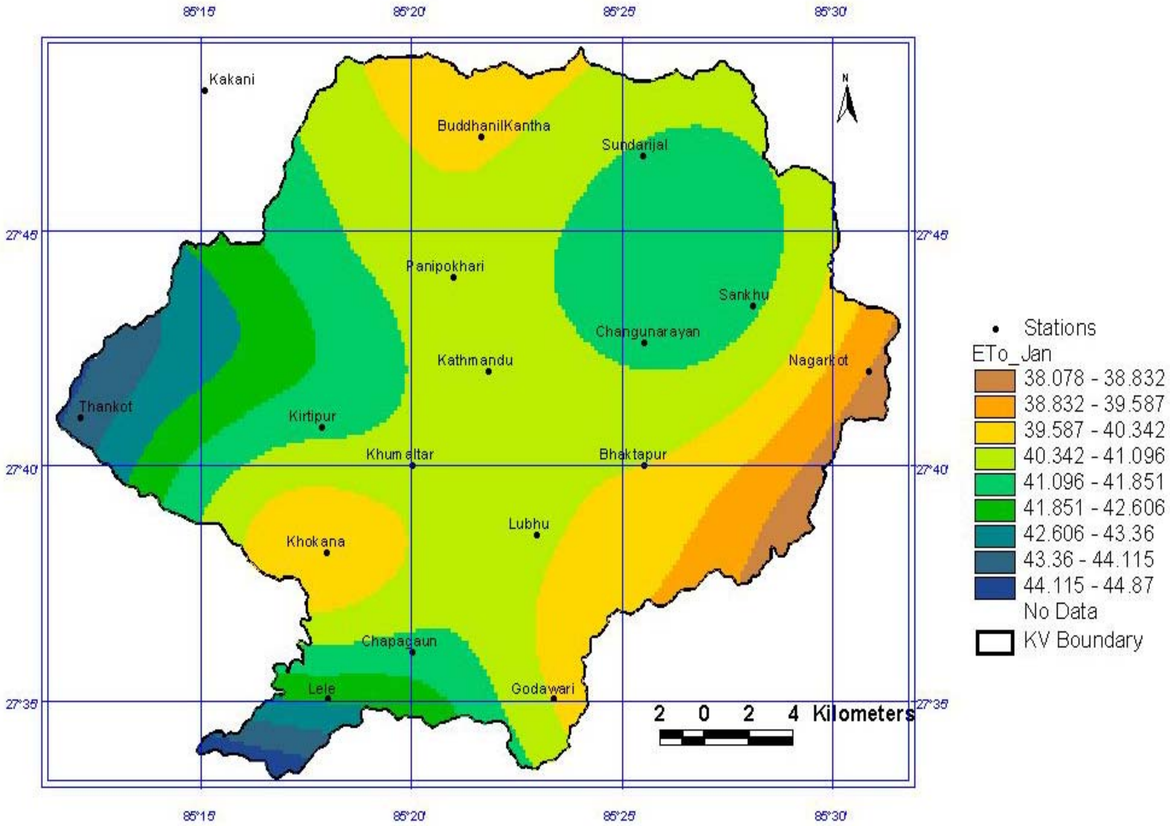


Figure 40: Estimated Total (Reference grass Evapotranspiration) ETo in mm in January

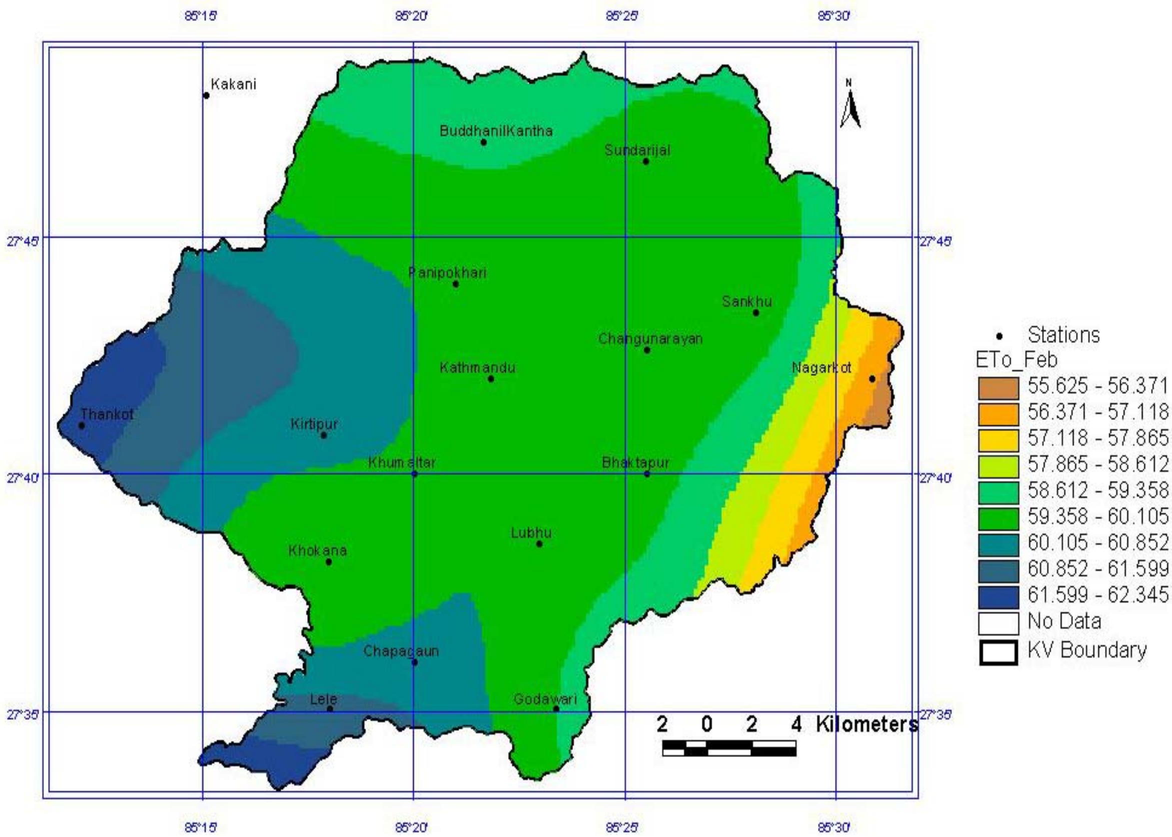


Figure 41: Estimated Total ETo (mm) in February

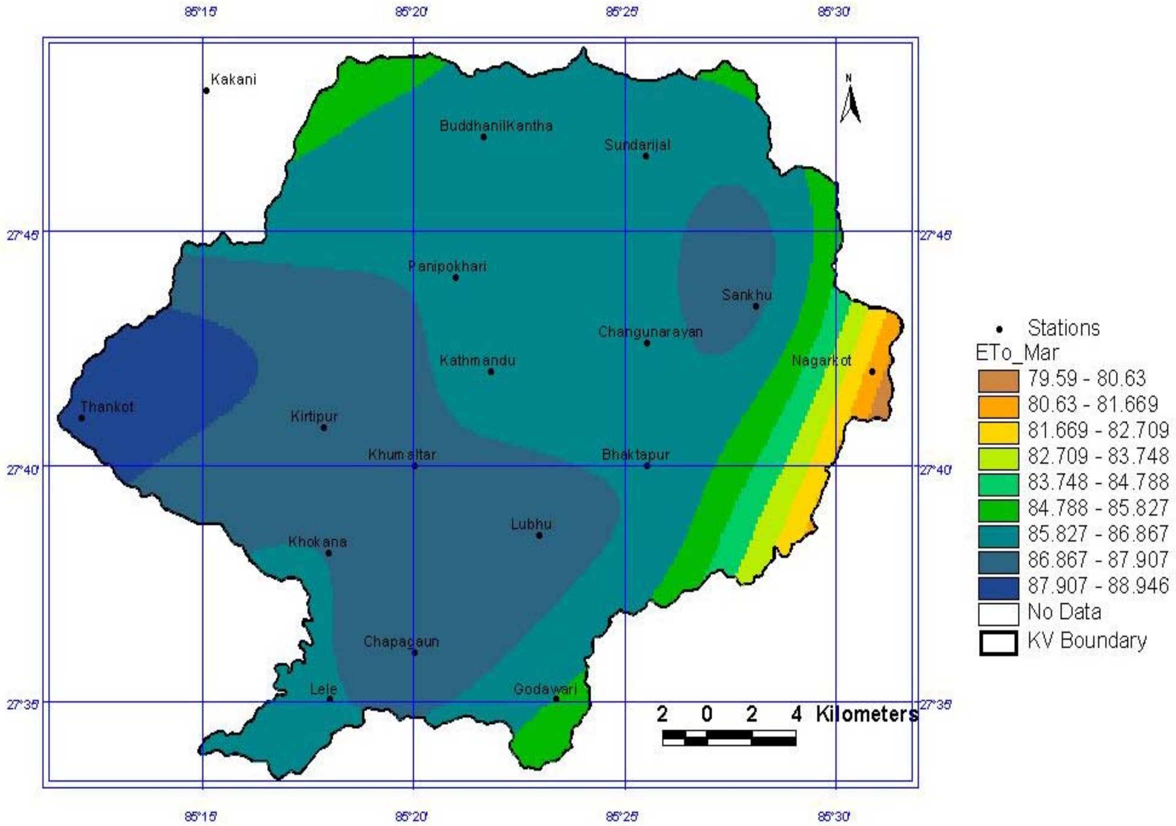


Figure 42: Estimated Total ETo (mm) in March

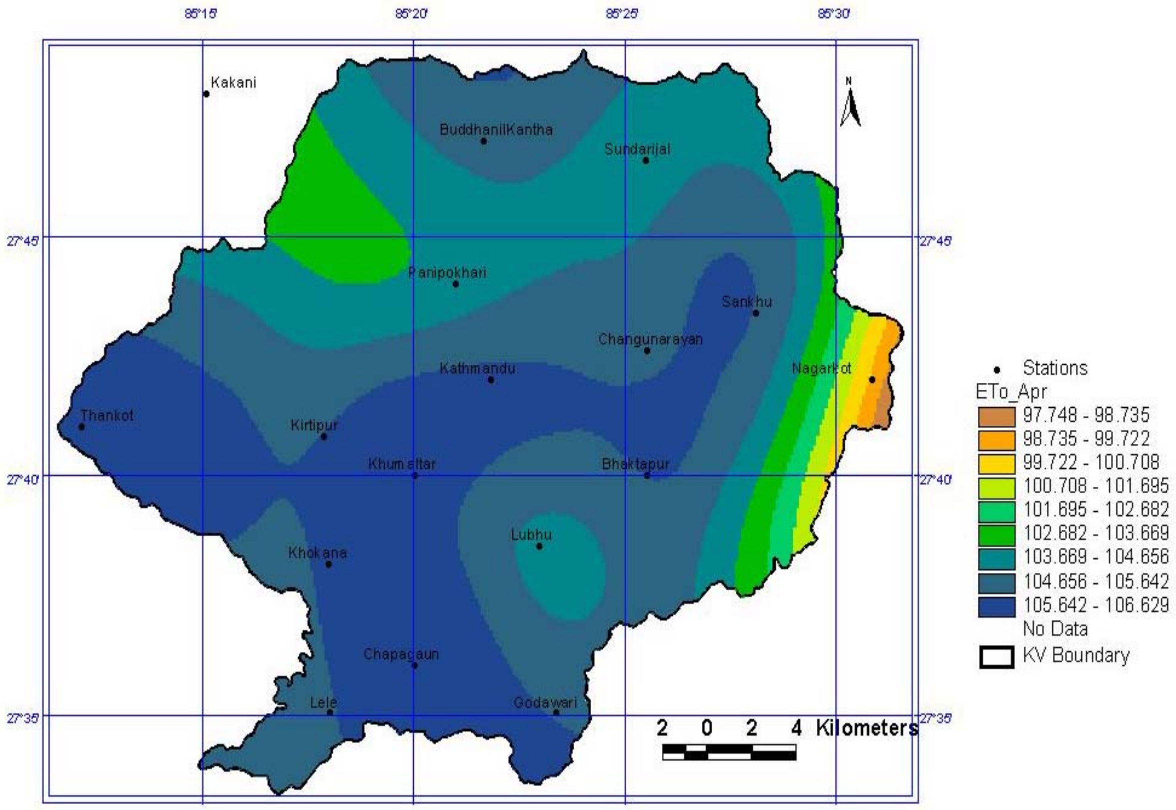


Figure 43: Estimated Total ETo (mm) in April

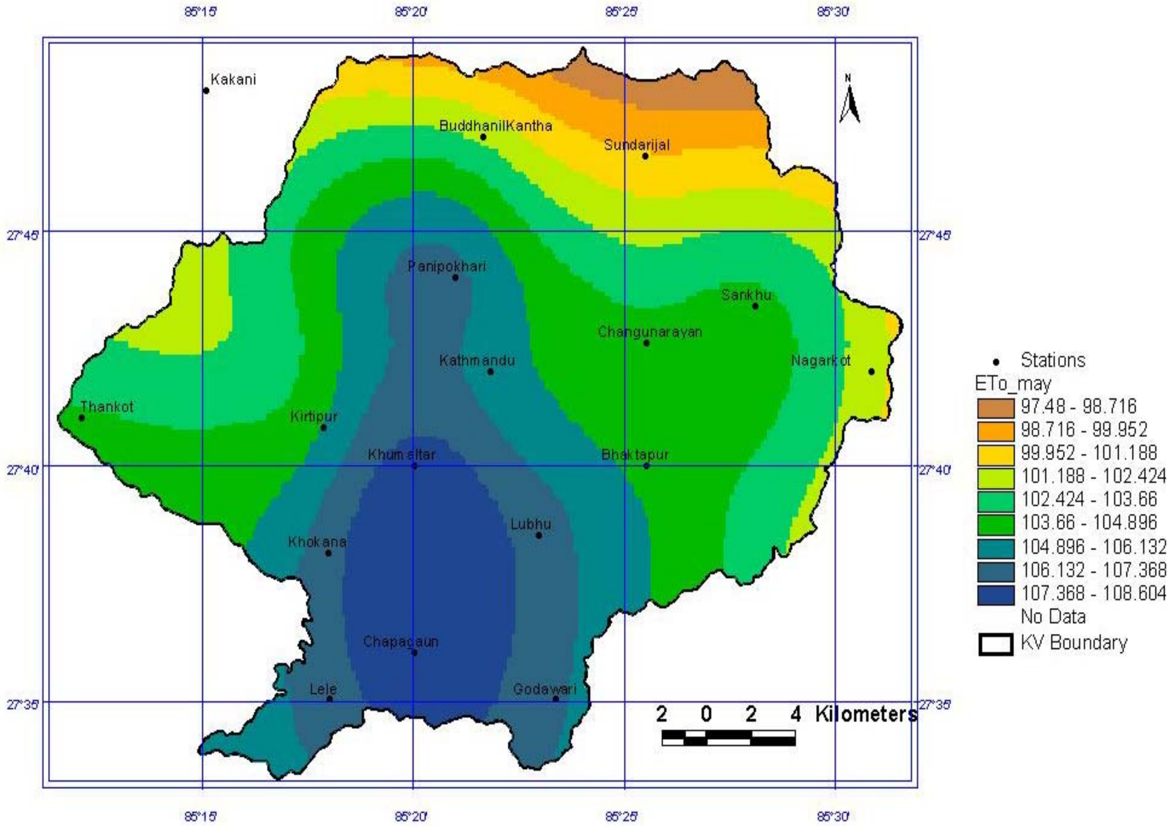


Figure 44: Estimated total ETo (mm) in May

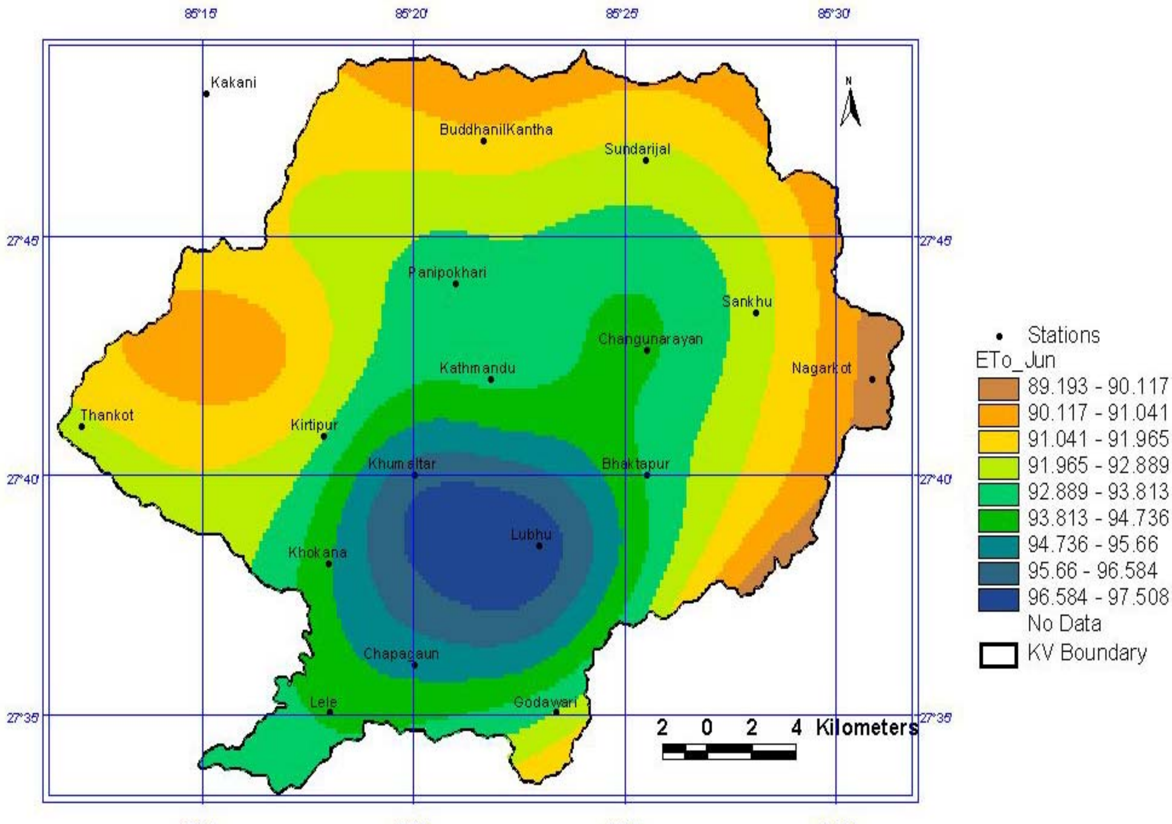


Figure 45: Estimated Total ETo (mm) in June

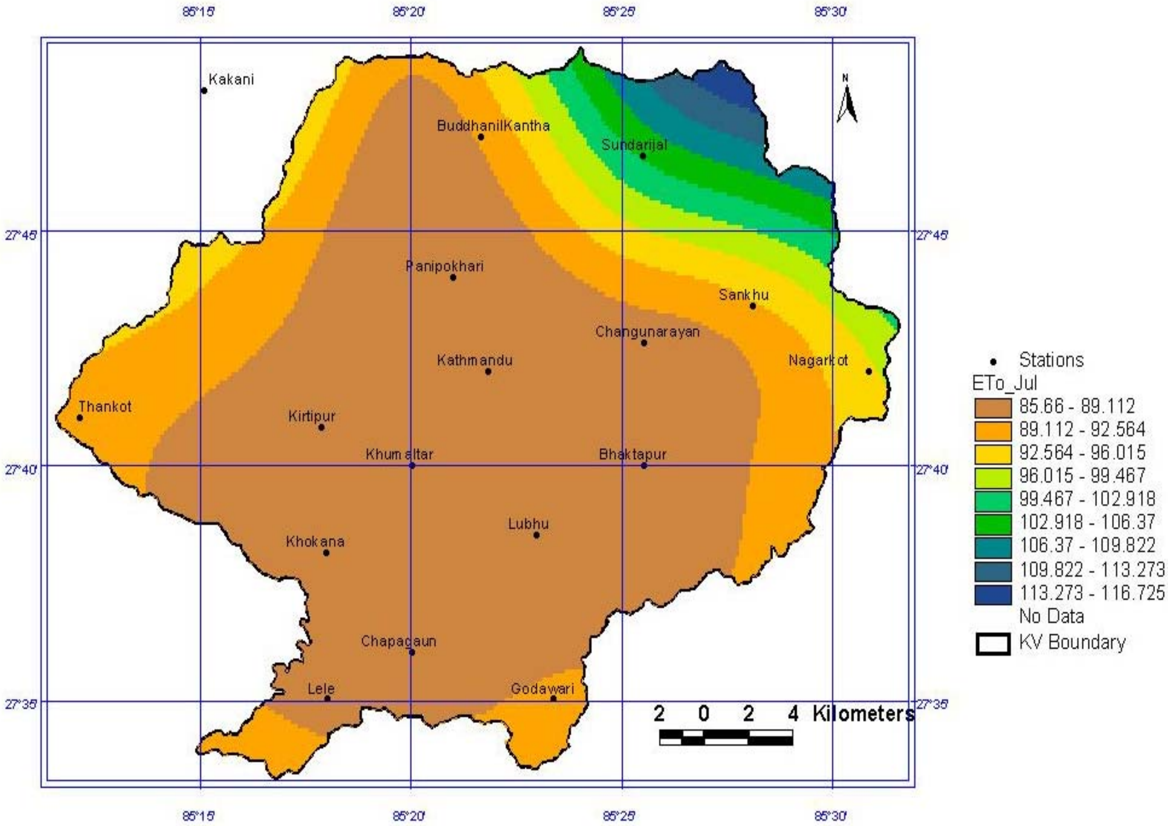


Figure 46: Estimated Total ETo (mm) in July

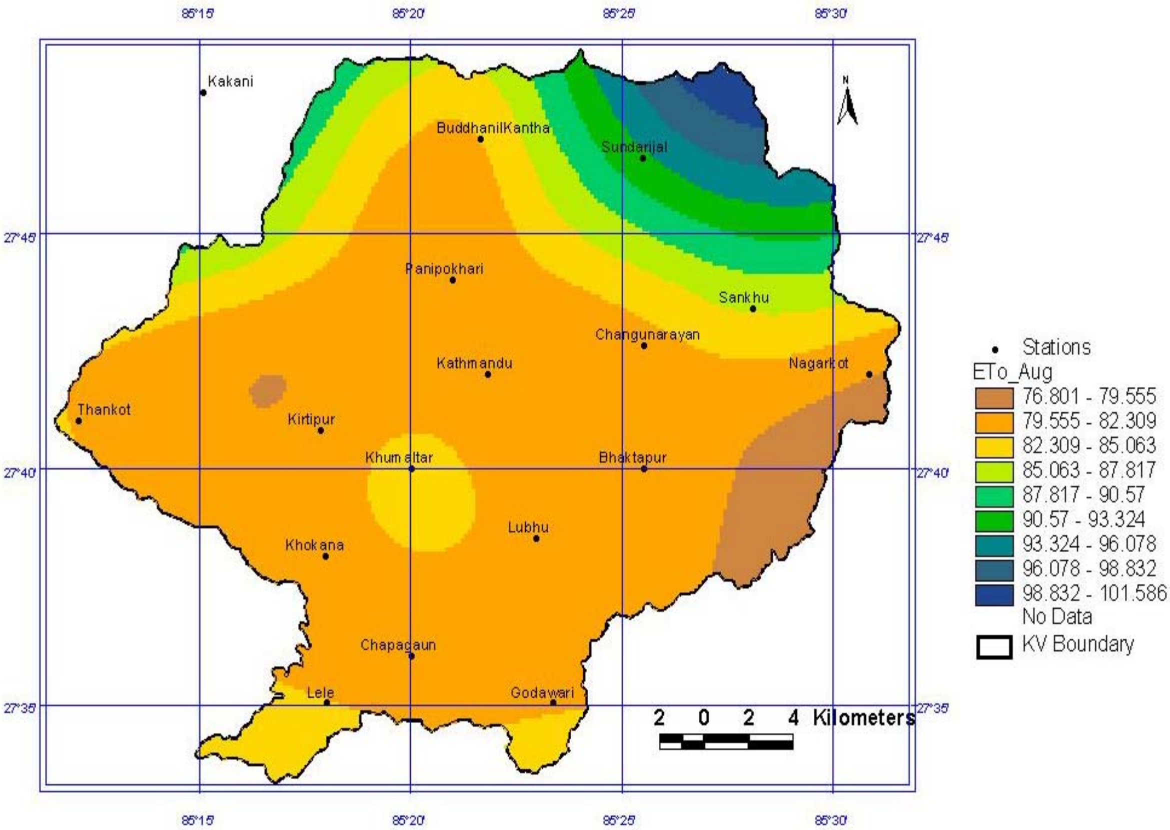


Figure 47: Estimated Total ETo (mm) in August

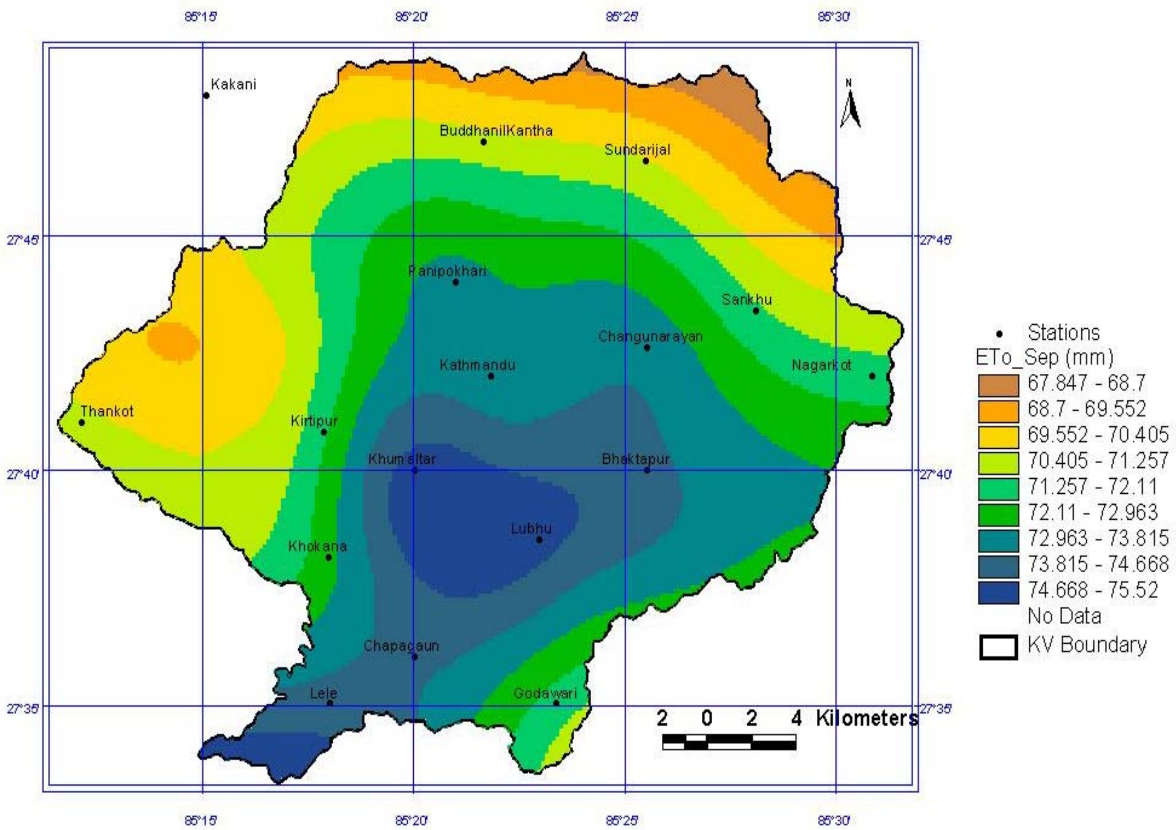


Figure 48: Estimated Total ETo (mm) in September

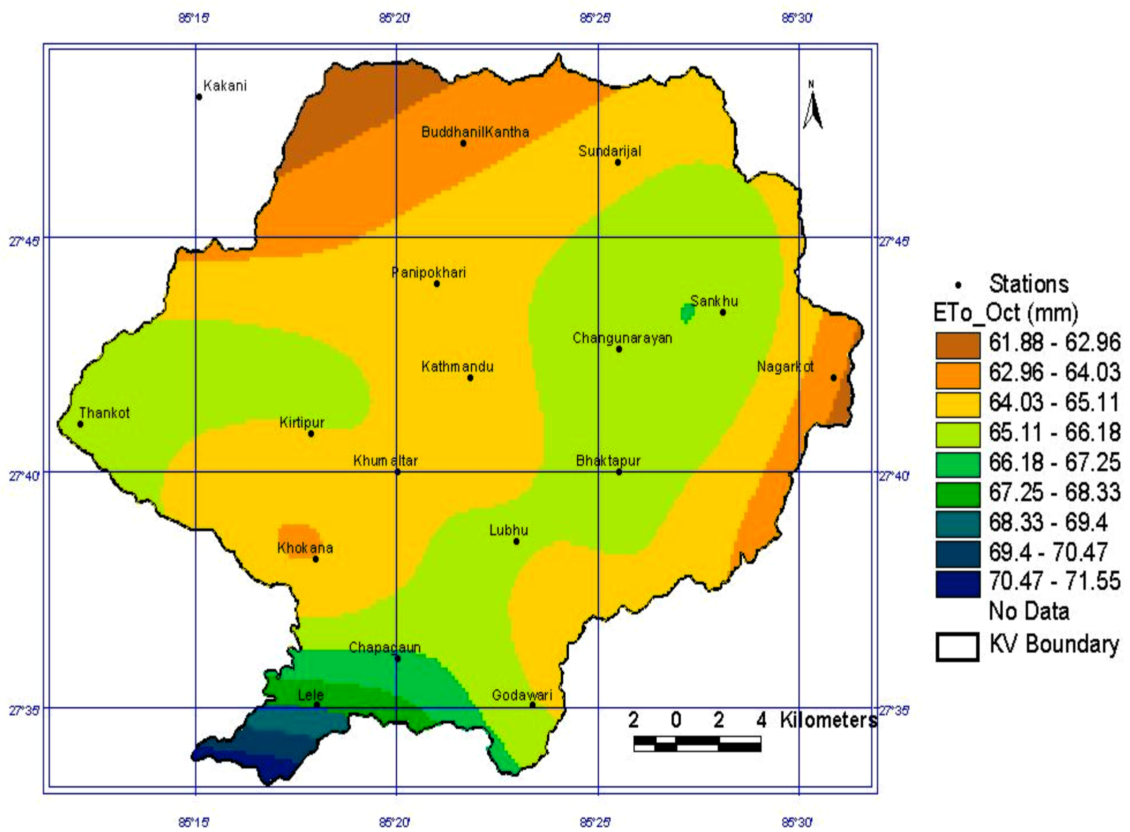


Figure 49: Estimated Total ETo (mm) in October

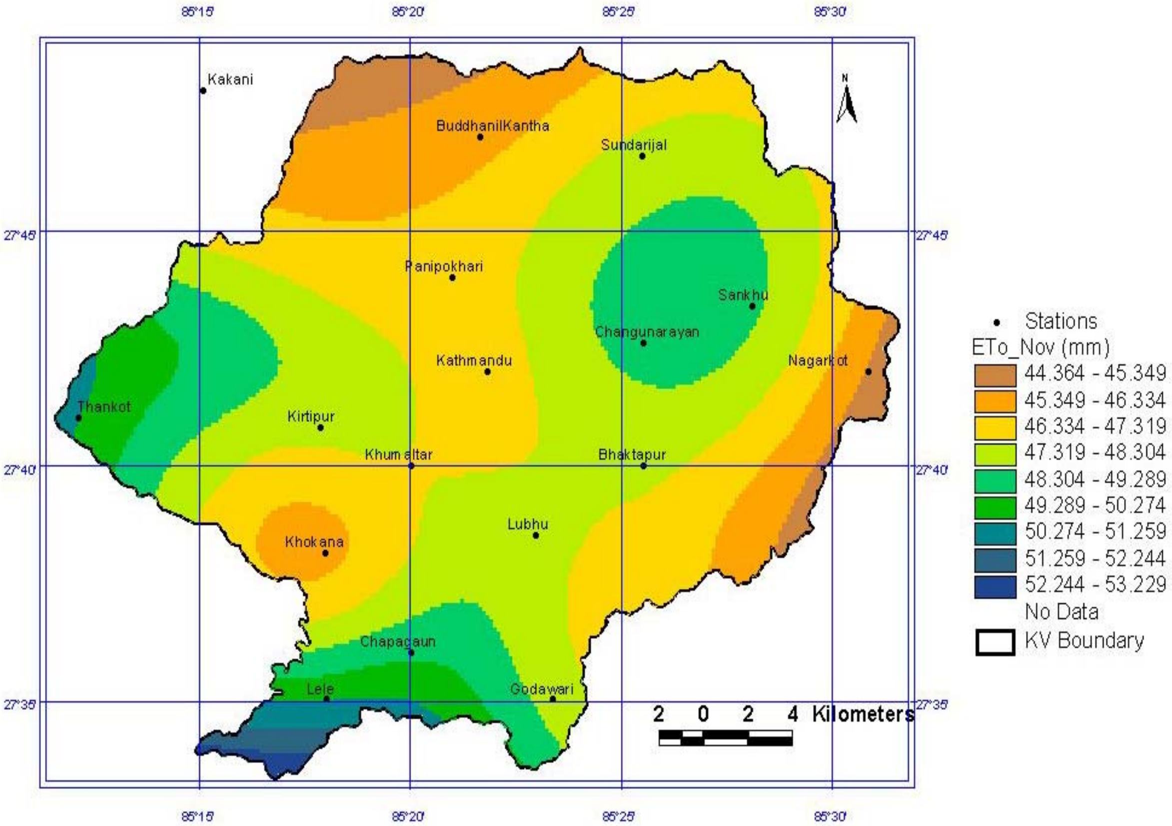


Figure 50: Estimated Total ETo (mm) in November

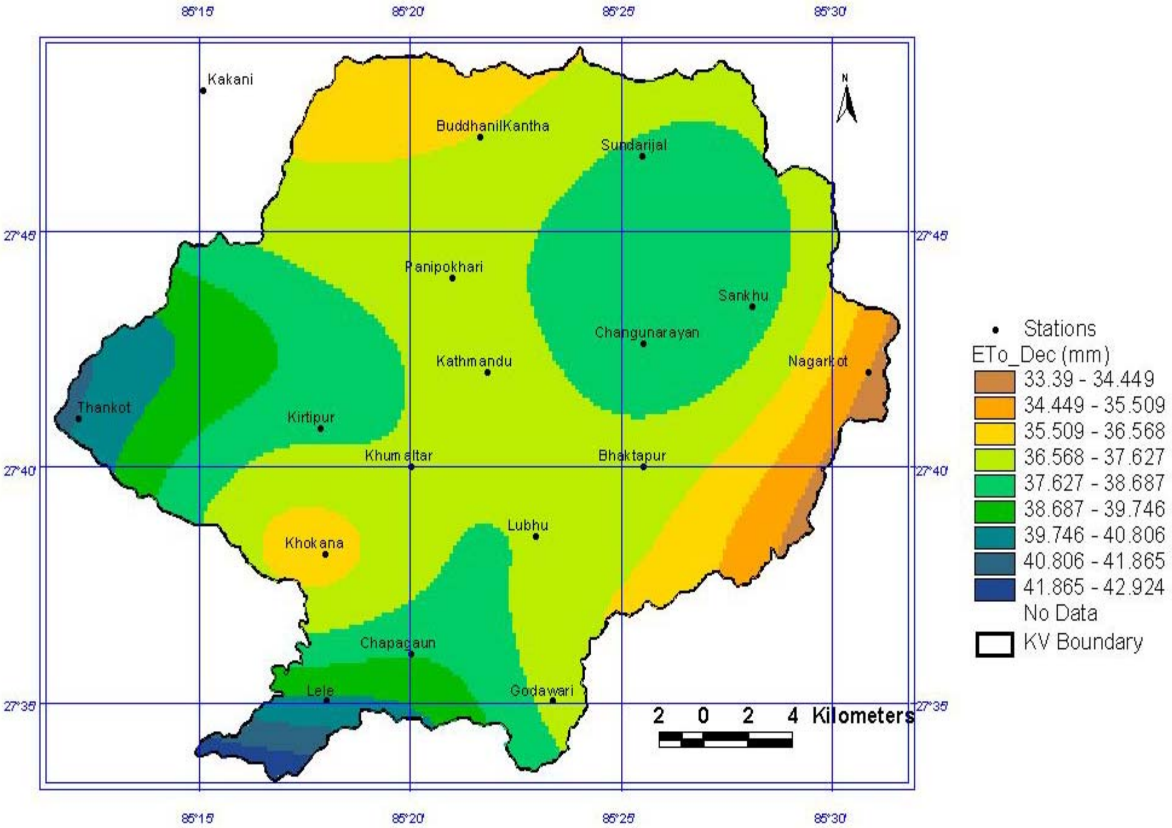


Figure 51: Estimated Total ETo (mm) in December

CHAPTER EIGHT

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

Evaporative depletion is the one of the key component in water balance and hydrological & Environmental modeling. Estimation of Reference Evapotranspiration over Kathmandu valley has been carried out using FAO Penman Monteith equation. For the data scarce condition various models were used to expand the required climatic parameters at the seventeen rainfall points in Kathmandu valley. Solar and Net radiation are the parameters that do not available easily and are very difficult to estimate. The estimation of solar radiation, net radiation and Reference Evapotranspiration for each of the selected seventeen locations in the Kathmandu valley watershed has been carried out using the guidelines and reliable relations reported by Allen et. al. (1998).

The climatic models developed for temperature, wind and sunshine are quite encouraging. The estimated values are quite closed to the measured values. In Kathmandu valley, the seasonal variation of different meteorological parameters and similar annual trends of different climatic parameters have been reported. High temperature, low humidity, low rainfall is found in pre monsoon, whereas high humidity, high wind speed, high rainfall is found in monsoon. Post monsoon is characterized by low rainfall and high solar radiation but latitudinal cooling makes temperature lower. The wind run is more or less uniform throughout the year in the valley base but not uniform at hilly region.

Solar Radiation ranges from 154.88 W/m^2 in December to 250.77 W/m^2 in April with average 201 W/m^2. Net radiation ranges from 34.61 W/m^2 in December to 116.59 W/m^2 in May with annual average of 82.55 W/m^2.

The study basically deals with the effect of the climatic factors on the Reference Evapotranspiration. Evapotranspiration was calculated applying the FAO-Penman Monteith method with the proposed equations for estimation of missing climatological data. The estimated evapotranspiration are also compared with the Class A pan data and the results are fairly good and their relationships are shown. The high sunshine hour, evaporation and evapotranspiration is found in March, April and May. The monthly rise and fall of evaporation and evapotranspiration pattern are similar. In Kathmandu valley, the daily ETo ranges from 1.26 mm/day, in December, to about 3.62 mm/day in the month of April, with average of 2.5 mm/day

The maximum monthly ETo is observed in the month of April and May whereas minimum monthly ETo is observed in the month of December. Five months of water surplus (lesser ETo and higher rainfall) from May to September and Seven months of water deficit (higher monthly ETo and less rainfall) from October to April have been accounted. Annual reference evapotranspiration rates in Kathmandu valley range from 800 to 1000 mm per annum at different stations. The average annual reference evapotranspiration for Kathmandu valley is 886.20 mm.

The maps of spatial patterns of distribution of climatic variables over Kathmandu valley have shown that more ET has been observed in the sun-facing surfaces than the surface opposite to sun. But, variations of ETo with the elevation can not be observed clearly. The assessment of ET becomes more complex in difficult topography of the mountainous catchments as ET varies significantly according to elevation, surface steepness and orientation in mountain environment. Hence, a correction using mountain radiation model is considered necessary to dealing with sloping surface. The monthly ETo maps show that the estimated values are more reliable and applicable for the humid months which experienced higher ETo rate than for lesser ETo months. More errors in ETo valus can be expected in the months of the lower ETo.

It has to be noted that although the values calculated above seem to be plausible in comparison with measured data and experimental data and data from other studies, evapotranspiration remains a subject where much more work is required to reach conclusive answers. In order to improve the quality of the evapotranspiration data, the automatic weather stations data should be published and tested.

The Penman-Monteith equation for the determination of Reference Evapotranspiration is appropriate method for upper Bagmati basin. Daily values of solar, net radiation and ET for each month provide the information of energy and radiation balance and water balance in Kathmandu valley. Research concludes that the most accurate method of determining ET depends upon the long term and micro stage study. For our purpose, which was to estimate ET from limited data Penman/Monteith method appeared to be the most reliable method. But some correction and more experiments are needed for different soil water condition.

8.2 Implications and Recommendations for further study

The empirical relation for the estimation of Maximum and minimum temperature, Wind speed, Sunshine ratio developed by Tahal consulting Engineers 2002 should be tested and it should be modified, if necessary, to represent whole Nepal climatic condition. Improvement should be there in these models to minimize the sparse and irregularity of estimated data.

It is recommended to develop software assembling the empirical climatic models and Penman-Monteith equation for estimating evapotranspiration so that it will be easy for the climatic database and other research work.

Research incorporating numerical weather prediction technique is essential. Using the same method, whole evapotranspiration and net radiation map should be prepared.

From the experimental estimation of Evapotranspiration, hourly data must be collected during the observation. Climatological stations rather than precipitation stations are essential in order to estimate evapotranspiration more effectively. Great care should be taken while celebrating instrument or downloading. Caution is recommended when using the penman-Monteith model for estimation of grass evapotranspiration. Sophisticated, hourly and trustworthy meteorological data is required for the method when estimating ETo.

Grass water need is an important concept for planning and management of irrigation. It is directly related to crop water need. In order to develop irrigation system, estimation of evapotranspiration and irrigation water is necessary.

The research outputs and the possible area of their implementation are tabulated as below.

Research outputs	**Area of implementation**
ETo Maps	:- Ecology, water balance, Plant, climate, Agriculture, drought, lake studies,
Radiation Maps	:- Crop, Climate, Ecology, snow, Climate change, micrometeorology, solar power engineering, water purification by SODIS
Literature Review	:- For researchers and projects
Methodology	:- Calculation procedure
Tables	:- Obtaining different parameters.

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APPENDICES

Appendix 1: Extraterrestrial Radiation (R_a) in mm/day

Stn Index	Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual mean
1030	Kath Airport	9.3	11.3	13.5	15.4	16.5	16.9	16.7	15.8	14.2	12.1	9.9	8.8	13.36
1022	Godawari	9.3	11.3	13.5	15.4	16.5	16.9	16.7	15.8	14.2	12.1	9.9	8.8	13.36
1071	Buddhanilkantha	9.2	11.2	13.4	15.4	16.5	16.9	16.7	15.8	14.2	12.0	9.8	8.7	13.31
1029	Khumaltar	9.3	11.3	13.5	15.4	16.5	16.9	16.7	15.8	14.2	12.1	9.9	8.8	13.36
1043	Nagarkot	9.3	11.3	13.5	15.4	16.5	16.9	16.7	15.8	14.2	12.1	9.9	8.8	13.36
1039	Panipokhari	9.3	11.3	13.5	15.4	16.5	16.9	16.7	15.8	14.2	12.1	9.9	8.8	13.36
1075	Lele	9.3	11.3	13.5	15.4	16.5	16.9	16.7	15.8	14.2	12.1	9.9	8.8	13.36
1061	Lubhu	9.3	11.3	13.5	15.4	16.5	16.9	16.7	15.8	14.2	12.1	9.9	8.8	13.36
1060	Chapagaun	9.3	11.3	13.5	15.4	16.5	16.9	16.7	15.8	14.2	12.1	9.9	8.8	13.36
1052	Bhakatapur	9.3	11.3	13.5	15.4	16.5	16.9	16.7	15.8	14.2	12.1	9.9	8.8	13.36
1007	Kakani	9.2	11.2	13.4	15.4	16.5	16.9	16.7	15.8	14.2	12.0	9.8	8.7	13.31
1015	Thankot	9.3	11.3	13.5	15.4	16.5	16.9	16.7	15.8	14.2	12.1	9.9	8.8	13.36
1074	Sundarijal	9.2	11.2	13.4	15.4	16.5	16.9	16.7	15.8	14.2	12.0	9.8	8.7	13.31
1035	Sankhu	9.3	11.3	13.5	15.4	16.5	16.9	16.7	15.8	14.2	12.1	9.9	8.8	13.36
1073	Khokana	9.3	11.3	13.5	15.4	16.5	16.9	16.7	15.8	14.2	12.1	9.9	8.8	13.36
1059	Changunarayan	9.2	11.2	13.4	15.4	16.5	16.9	16.7	15.8	14.2	12	9.8	8.7	13.31
1021	Kirtipur	9.3	11.3	13.5	15.4	16.5	16.9	16.7	15.8	14.2	12.1	9.9	8.8	13.36
KV	**Average**	**9.27**	**11.27**	**13.47**	**15.40**	**16.50**	**16.90**	**16.70**	**15.80**	**14.20**	**12.07**	**9.87**	**8.77**	**13.35**

(Source: Pokhrel 1998)

Appendix 2 : Average monthly rainfall (mm) of the Valley (1971-2000) & Annual total rainfall (mm)

Msld	Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual total (mm)
1007	Kakani	16.2	24.3	39.8	71.5	186.3	474.8	674.3	693.3	388.4	81.6	9.3	16.0	2675.9
1015	Thankot	19.7	24.9	39.4	73.0	143.5	314.9	534.8	476.5	305.0	73.3	12.0	21.4	2038.5
1021	Kirtipur(Bagbani)	16.0	20.3	34.2	64.9	128.8	283.0	441.5	394.0	229.5	58.6	12.8	17.8	1701.6
1022	Godavari	15.5	22.2	35.5	56.7	128.0	322.0	523.4	445.4	270.8	68.7	9.7	20.8	1918.7
1029	Khumaltar	14.1	17.6	25.5	53.3	101.6	211.1	310.8	251.0	153.6	51.3	6.1	18.3	1214.2
1030	Ktm Airport	13.7	17.5	30.3	56.9	115.6	262.2	356.5	318.6	186.9	56.7	7.9	15.1	1437.8
1035	Sankhu	11.8	24.7	29.1	55.4	145.7	335.8	540.8	530.4	286.3	65.1	10.9	12.0	2048.1
1039	PaniPokhari	13.7	17.6	31.1	69.9	122.1	270.0	376.8	351.3	192.2	57.7	8.7	13.1	1524.1
1043	Nagarkot	12.5	17.6	29.8	55.7	139.9	337.7	477.8	475	263.2	75.8	10.0	12.2	1907.1
1052	Bhaktapur	13.0	19.4	30.3	54.7	137.1	271.0	379.5	344.3	186.2	55.4	6.4	15.7	1513
1059	Changunarayan	15.6	21.3	32.9	60.9	146.5	277.8	428.2	409.8	222.9	63.0	9.2	15.7	1703.7
1060	Chapagaon	15.7	17.8	30.8	51.0	97.6	249.6	404	321.4	203.6	52.8	5.3	19.4	1468.9
1061	Lubhu	16.1	14.7	22.5	72.1	110.5	202.2	364.5	303.6	167.0	63.2	15.1	26.2	1377.7
1071	Buddhanilkantha	13.6	20.1	35.8	66.8	159.7	336.0	506.1	480.9	262.6	65.1	8.7	15.4	1970.8
1073	Khokana	15.6	18.9	29.5	58.4	106.9	239.7	376.8	305.6	198.9	57.3	7.7	18.9	1434.2
1074	Sundarijal	17.1	25.6	43.5	78.1	203.1	403.6	668.3	638.0	349.0	76.1	12.4	18.6	2533.4
1075	Lele	18.0	20.0	49.0	68.0	115.0	290.7	459.8	452.1	216.0	30.9	56.8	7.0	1783.25
KV	**Average**	**14.8**	**20.3**	**32.8**	**60.9**	**134.6**	**297.3**	**453.9**	**413.4**	**238.3**	**63.1**	**8.7**	**16.7**	**1779.5**

(Source: Devkota, L. P., SOHAM-Nepal, 2005 and DHM)

Appendix 3 : Constants of the Sunshine Model

Group No.	A	B x 10^2	C x 10^5
1	0.81	-0.14	0.11
2	0.85	-0.24	0.36
3	0.87	-0.25	0.4
4	0.9	-0.29	0.36
5	0.8	-0.11	0.08
6	***0.79***	***-0.25***	***0.34***
7	0.76	-0.1	0.06
8	0.69	-0.15	0.12
9	0.76	-0.07	0.03
10	0.72	-0.26	0.34

(Source: Pokhrel 1998)

Appendix 4 : Constants for the Maximum Temperature Model

Month	A	B	C	$D \times 10^{-3}$	R^2
Jan	-90.95	1.77	0.78	-5.80	0.93
Feb	-78.62	1.57	0.74	-6.70	0.96
Mar	-27.08	0.82	0.44	-7.00	0.96
Apr	45.63	0.07	-0.13	-7.40	0.97
May	70.32	0.38	-0.52	-6.90	0.95
Jun	-6.63	1.61	-0.02	-6.40	0.93
Jul	-85.39	2.29	0.67	-5.80	0.90
Aug	-86.21	2.04	0.77	-5.80	0.92
Sep	-76.17	2.05	0.63	-5.90	0.93
Oct	-39.44	1.31	0.43	-6.30	0.95
Nov	-41.99	1.12	0.49	-6.30	0.95
Dec	-52.17	1.18	0.53	-5.50	0.94

(Source: Pokhrel 1998)

Appendix 5 : Constants for minimum temperature model

Month	A	$B \times 10^{-2}$	$C \times 10^{-2}$	$D \times 10^{-4}$	R^2
Jan	40.20	-75.00	-11.30	-38.20	0.76
Feb	41.23	-68.10	-12.60	-41.10	0.78
Mar	63.94	-97.60	-25.20	-42.30	0.79
Apr	144.42	-209.10	-79.40	-44.40	0.82
May	141.49	-164.70	-86.00	-53.30	0.93
Jun	90.36	-77.80	-51.20	-51.80	0.98
Jul	35.29	-10.70	-14.40	-51.30	0.99
Aug	37.19	-2.80	-12.10	-51.10	0.98
Sep	45.90	-32.80	-13.90	-52.70	0.98
Oct	79.39	-130.90	-26.30	-51.00	0.93
Nov	77.99	-132.70	-31.20	-42.00	0.80
Dec	61.18	-114.40	-21.80	-38.00	0.73

(Source: Pokhrel 1998)

Appendix 6: Recorded Maximum Temperature in ^{0}C

Stn Index	Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1022	Godawari	15.64	17.81	21.89	25.27	26.43	26.19	25.64	25.46	24.38	23.11	20.16	16.53
1029	Khumaltar	17.97	19.89	24.08	27.29	28.19	28.40	27.58	27.51	27.07	25.89	23.28	19.73
1030	Kath Airport	17.58	19.79	23.46	26.06	26.48	26.52	25.98	26.09	25.83	24.66	21.98	18.78
1039	Panipokhari	15.51	17.63	21.84	24.41	25.60	25.64	25.34	25.46	24.68	23.11	20.07	16.97
1043	Nagarkot	11.91	13.65	17.86	21.18	21.55	21.37	20.81	20.62	20.61	19.22	16.54	13.27
1071	Buddhanilkantha	15.46	17.25	21.12	24.01	25.17	25.05	24.63	24.75	24.32	22.64	20.13	17.11
	Average	**15.68**	**17.67**	**21.71**	**24.70**	**25.57**	**25.53**	**25.00**	**24.98**	**24.48**	**23.10**	**20.36**	**17.06**

(Source: DHM)

Appendix 7 : Recorded Minimum Temperature in ^{0}C

Stn Index	Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1030	Kath Airport	1.93	3.97	7.16	10.47	14.62	17.52	18.41	18.18	16.83	12.16	7.35	3.33
1022	Godawari	2.83	4.71	8.20	11.46	14.83	17.67	18.77	18.58	16.90	13.03	8.05	4.21
1071	Buddhanilkantha	3.65	5.63	8.96	12.54	15.85	18.95	19.81	19.62	18.05	13.61	9.47	5.04
1029	Khumaltar	1.55	3.53	6.94	10.47	15.53	19.23	20.38	20.14	18.54	13.30	7.62	2.89
1043	Nagarkot	2.17	3.43	6.60	9.73	11.34	13.35	14.05	14.06	12.98	10.15	6.66	3.60
1039	Panipokhari	2.40	4.78	7.93	11.31	14.58	16.96	17.82	17.80	16.79	12.82	8.40	4.22
	Average	**2.42**	**4.34**	**7.63**	**11.00**	**14.46**	**17.28**	**18.21**	**18.06**	**16.68**	**12.51**	**7.93**	**3.88**

(Source: DHM)

Appendix 8 : Recorded Mean monthly temperature in ^{0}C

Stn Index	Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1022	Godawari	9.24	11.26	15.04	18.37	20.63	21.93	22.21	22.02	20.64	18.07	14.11	10.37
1029	Khumaltar	9.76	11.71	15.51	18.88	21.86	23.82	23.98	23.83	22.81	19.60	15.45	11.31
1030	Kath Airport	9.75	11.88	15.31	18.26	20.55	22.02	22.20	22.14	21.33	18.41	14.66	11.05
1039	Panipokhari	8.96	11.20	14.89	17.86	20.09	21.30	21.58	21.63	20.73	17.97	14.23	10.59
1043	Nagarkot	7.04	8.54	12.23	15.45	16.44	17.36	17.43	17.34	16.80	14.68	11.60	8.44
1071	Buddhanilkantha	9.56	11.44	15.04	18.27	20.51	22.00	22.22	22.19	21.18	18.12	14.80	11.07
	Average	**9.05**	**11.00**	**14.67**	**17.85**	**20.01**	**21.40**	**21.60**	**21.52**	**20.58**	**17.81**	**14.14**	**10.47**

(Source: DHM)

Appendix 9 : Estimated maximum temperature in ^{0}C

Stn Index	Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1007	Kakani	12.78	14.28	18.78	21.22	22.31	23.21	23.42	24.17	22.35	20.63	17.92	14.46
1015	Thankot	15.05	16.97	21.70	24.43	25.29	25.80	25.63	26.41	24.64	23.19	20.49	16.69
1021	Kirtipur	16.67	18.83	23.60	26.39	27.07	27.50	27.24	28.03	26.27	24.91	22.22	18.20
1022	Godawari	16.36	18.50	23.31	26.10	26.73	27.11	26.87	27.70	25.92	24.60	21.93	17.94
1029	Khumaltar	16.75	18.92	23.70	26.48	27.15	27.57	27.31	28.11	26.34	24.99	22.31	18.28
1030	Kath Airport	16.92	19.09	23.84	26.58	27.24	27.71	27.49	28.28	26.51	25.14	22.45	18.41
1035	Sankhu	16.44	18.50	23.14	25.74	26.42	27.06	27.03	27.82	26.02	24.54	21.85	17.91
1039	Panipokhari	16.97	19.14	23.87	26.60	27.27	27.77	27.56	28.34	26.58	25.18	22.48	18.45
1043	Nagarkot	12.24	13.66	18.12	20.45	21.45	22.41	22.79	23.60	21.73	19.99	17.31	13.94
1052	Bhakatapur	16.94	19.12	23.88	26.62	27.24	27.70	27.49	28.29	26.52	25.16	22.48	18.44
1059	Changunarayan	15.84	17.82	22.46	25.05	25.80	26.46	26.44	27.22	25.43	23.92	21.22	17.36
1060	Chapagaun	16.06	18.16	22.96	25.75	26.44	26.83	26.59	27.40	25.63	24.29	21.61	17.66
1061	Lubhu	16.81	18.99	23.77	26.54	27.17	27.60	27.36	28.16	26.39	25.05	22.37	18.33
1071	Buddhanilkantha	16.98	19.13	23.81	26.49	27.17	27.75	27.60	28.37	26.60	25.16	22.45	18.43
1073	Khokana	17.45	19.75	24.62	27.51	28.11	28.40	28.00	28.80	27.06	25.80	23.11	18.97
1074	Sundarijal	16.18	18.20	22.84	25.44	26.17	26.83	26.78	27.56	25.77	24.28	21.58	17.67
1075	Lele	15.17	17.14	21.93	24.71	25.48	25.90	25.69	26.51	24.72	23.35	20.68	16.83
KV	**Average**	**15.98**	**18.01**	**22.73**	**25.42**	**26.15**	**26.68**	**26.55**	**27.34**	**25.56**	**24.13**	**21.44**	**17.53**

(Source: Computed from Multiple regression)

Appendix 10 : Estimated Minimum Temperature in ^0C

Stn Index	Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1007	Kakani	1.01	2.65	5.73	9.20	12.24	14.90	15.66	15.75	14.96	11.02	6.87	2.68
1015	Thankot	1.43	3.30	6.59	10.01	13.94	16.97	17.98	17.89	16.65	12.27	7.24	2.96
1021	Kirtipur	2.30	4.34	7.67	11.08	15.03	18.07	19.07	18.90	17.46	12.97	8.04	3.77
1022	Godawari	3.37	5.11	8.55	11.66	14.48	17.01	17.99	17.73	15.98	12.40	7.93	4.61
1029	Khumaltar	2.62	4.62	7.97	11.32	15.01	17.93	18.92	18.72	17.21	12.91	8.11	4.04
1030	Kath Airport	2.72	4.76	8.07	11.47	15.13	18.04	18.98	18.80	17.34	12.98	8.33	4.17
1035	Sankhu	3.29	5.18	8.44	11.76	14.56	17.11	17.91	17.74	16.31	12.45	8.47	4.70
1039	Panipokhari	2.45	4.58	7.84	11.32	15.25	18.28	19.21	19.06	17.69	13.11	8.38	3.97
1043	Nagarkot	3.31	4.43	7.60	10.60	11.19	12.78	13.34	13.33	12.12	9.88	7.14	4.63
1052	Bhakatapur	3.30	5.24	8.58	11.86	14.99	17.67	18.58	18.36	16.76	12.79	8.41	4.66
1059	Changunarayan	2.98	4.80	8.06	11.36	14.15	16.68	17.50	17.36	15.97	12.18	8.12	4.40
1060	Chapagaun	2.86	4.64	8.05	11.23	14.38	17.05	18.05	17.83	16.19	12.39	7.73	4.17
1061	Lubhu	3.09	5.01	8.39	11.65	14.92	17.66	18.62	18.39	16.77	12.77	8.20	4.44
1071	Buddhanilkantha	2.34	4.53	7.73	11.30	15.30	18.37	19.26	19.13	17.90	13.16	8.54	3.92
1073	Khokana	2.59	4.70	8.10	11.47	15.59	18.69	19.77	19.53	17.90	13.36	8.19	3.99
1074	Sundarijal	2.71	4.70	7.89	11.35	14.58	17.31	18.11	18.00	16.76	12.55	8.42	4.24
1075	Lele	2.61	4.25	7.66	10.79	13.72	16.31	17.30	17.11	15.51	11.94	7.31	3.91
KV	**Average**	**2.64**	**4.52**	**7.82**	**11.14**	**14.38**	**17.11**	**18.01**	**17.86**	**16.44**	**12.42**	**7.97**	**4.07**

(Source: Computed from Multiple regression)

Appendix 11 : Estimated Mean monthly temperature in ^0C

Stn Index	Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1030	Kath Airport	9.51	11.57	15.18	18.32	20.62	22.04	22.28	22.21	21.17	18.30	14.60	10.89
1022	Godawari	9.44	11.48	15.00	18.15	19.95	20.99	21.26	21.08	19.73	17.34	13.67	10.27
1071	Buddhanilkantha	9.39	11.42	15.08	18.20	20.71	22.32	22.52	22.53	21.75	18.61	14.97	11.14
1029	Khumaltar	9.49	11.55	15.19	18.35	20.67	22.08	22.32	22.22	21.11	18.30	14.51	10.79
1043	Nagarkot	7.09	8.58	12.08	15.18	15.61	16.16	16.26	16.18	15.53	13.68	10.98	8.17
1039	Panipokhari	9.48	11.53	15.18	18.32	20.78	22.32	22.54	22.50	21.58	18.56	14.84	11.04
1075	Lele	8.83	10.75	14.41	17.65	19.48	20.63	20.84	20.65	19.46	17.10	13.35	9.85
1061	Lubhu	9.56	11.63	15.18	18.32	20.39	21.63	21.89	21.76	20.55	17.90	14.21	10.65
1060	Chapagaun	9.26	11.27	14.88	18.07	20.05	21.24	21.48	21.31	20.07	17.57	13.81	10.28
1052	Bhakatapur	9.58	11.66	15.16	18.25	20.26	21.46	21.72	21.62	20.45	17.78	14.21	10.70
1007	Kakani	7.19	8.73	12.64	15.93	17.77	19.26	19.29	19.29	19.04	16.30	12.93	9.26
1015	Thankot	8.58	10.45	14.31	17.62	20.02	21.62	21.77	21.67	20.85	18.01	14.12	10.24
1074	Sundarijal	9.00	10.94	14.52	17.61	19.66	21.03	21.21	21.22	20.46	17.57	14.19	10.59
1035	Sankhu	9.19	11.17	14.66	17.72	19.53	20.68	20.91	20.86	19.90	17.23	13.89	10.46
1073	Khokana	9.92	12.08	15.73	18.92	21.50	23.00	23.27	23.14	21.89	18.99	14.99	11.16
1059	Changunarayan	8.90	10.82	14.38	17.48	19.26	20.44	20.64	20.57	19.65	17.04	13.65	10.21
1021	Kirtipur	9.42	11.46	15.16	18.35	20.81	22.34	22.56	22.47	21.44	18.53	14.68	10.87
KV	**Average**	**9.05**	**11.01**	**14.63**	**17.79**	**19.83**	**21.13**	**21.34**	**21.25**	**20.27**	**17.58**	**13.98**	**10.39**

(Source: Computed from Multiple regression)

Appendix 12 : Mean monthly Saturated vapour pressure (e_s) in kPa

Stn Index	Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual mean
1007	Kakani	1.07	1.18	1.54	1.84	2.06	2.27	2.33	2.40	2.20	1.87	1.52	1.19	1.79
1015	Thankot	1.19	1.35	1.79	2.15	2.41	2.63	2.68	2.75	2.50	2.14	1.71	1.33	2.05
1021	Bagbani	1.31	1.50	1.98	2.38	2.64	2.87	2.91	2.99	2.71	2.32	1.88	1.45	2.24
1022	Godawari	1.26	1.45	1.86	2.29	2.57	2.71	2.73	2.70	2.49	2.16	1.72	1.35	2.11
1029	Khumaltar	1.37	1.55	2.00	2.45	2.79	3.05	3.04	3.02	2.86	2.43	1.95	1.53	2.34
1030	Kath. Airport	1.36	1.56	1.95	2.32	2.56	2.73	2.74	2.73	2.62	2.26	1.83	1.47	2.18
1035	Sankhu	1.32	1.51	1.97	2.34	2.55	2.76	2.81	2.89	2.61	2.26	1.86	1.45	2.20
1039	Panipokhari	1.24	1.44	1.84	2.20	2.47	2.61	2.64	2.65	2.51	2.15	1.73	1.38	2.07
1043	Nagarkot	1.05	1.17	1.51	1.86	1.96	2.04	2.03	2.02	1.96	1.73	1.43	1.16	1.66
1052	Bhakatapur	1.35	1.55	2.04	2.44	2.66	2.87	2.90	2.98	2.69	2.34	1.91	1.49	2.27
1059	Changunarayan	1.28	1.45	1.90	2.26	2.47	2.68	2.72	2.80	2.53	2.19	1.80	1.41	2.12
1060	Chapagaun	1.29	1.47	1.94	2.32	2.54	2.74	2.78	2.85	2.56	2.24	1.82	1.42	2.16
1061	Lubhu	1.34	1.53	2.02	2.42	2.65	2.86	2.89	2.97	2.67	2.33	1.90	1.47	2.25
1071	Buddhanilkantha	1.28	1.44	1.83	2.22	2.50	2.68	2.70	2.70	2.56	2.15	1.77	1.41	2.10
1073	Khokana	1.37	1.58	2.09	2.51	2.79	3.01	3.04	3.12	2.81	2.43	1.96	1.50	2.35
1074	Sundarijal	1.29	1.47	1.92	2.30	2.53	2.75	2.80	2.87	2.61	2.24	1.84	1.42	2.17
1075	Lele	1.23	1.39	1.84	2.20	2.42	2.60	2.64	2.71	2.44	2.13	1.73	1.36	2.06
KV	**Average**	**1.27**	**1.45**	**1.88**	**2.26**	**2.50**	**2.70**	**2.73**	**2.77**	**2.55**	**2.20**	**1.79**	**1.40**	**2.13**

(Source: Computed from Eq.5)

Appendix 13 : Mean monthly Actual vapour Pressure (e_a) in kPa

Stn Index	Location	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Annual mean
1007	Kakani	0.66	0.74	0.92	1.16	1.42	1.69	1.78	1.79	1.70	1.31	0.99	0.74	1.24
1015	Thankot	0.68	0.77	0.97	1.23	1.59	1.93	2.06	2.05	1.89	1.43	1.02	0.76	1.37
1021	Bagbani	0.72	0.83	1.05	1.32	1.71	2.07	2.21	2.18	1.99	1.50	1.08	0.80	1.45
1022	Godawari	0.75	0.85	1.09	1.35	1.69	2.02	2.17	2.14	1.93	1.50	1.08	0.83	1.45
1029	Khumal	0.68	0.79	1.00	1.27	1.76	2.23	2.39	2.36	2.14	1.53	1.05	0.75	1.50
1030	Kath Airport	0.70	0.81	1.01	1.27	1.66	2.00	2.12	2.09	1.92	1.42	1.03	0.78	1.40
1035	Sankhu	0.77	0.88	1.11	1.38	1.66	1.95	2.05	2.03	1.86	1.44	1.11	0.85	1.42
1039	Panipokhari	0.73	0.86	1.07	1.34	1.66	1.93	2.04	2.04	1.91	1.48	1.10	0.83	1.42
1043	Nagarkot	0.71	0.78	0.97	1.21	1.34	1.53	1.60	1.61	1.50	1.24	0.98	0.79	1.19
1052	Bhakatapur	0.77	0.89	1.12	1.39	1.70	2.02	2.14	2.11	1.91	1.48	1.10	0.85	1.46
1059	Changunarayan	0.76	0.86	1.08	1.34	1.61	1.90	2.00	1.98	1.82	1.42	1.08	0.84	1.39
1060	Chapagaun	0.75	0.85	1.08	1.33	1.64	1.94	2.07	2.04	1.84	1.44	1.05	0.82	1.41
1061	Lubhu	0.76	0.87	1.10	1.37	1.70	2.02	2.15	2.12	1.91	1.48	1.09	0.84	1.45
1071	Buddhanilkantha	0.79	0.91	1.14	1.45	1.80	2.19	2.31	2.28	2.07	1.56	1.19	0.87	1.55
1073	Khokana	0.74	0.85	1.08	1.35	1.77	2.16	2.31	2.27	2.05	1.53	1.09	0.81	1.50
1074	Sundarijal	0.74	0.85	1.06	1.34	1.66	1.98	2.08	2.06	1.91	1.45	1.10	0.83	1.42
1075	Lele	0.74	0.83	1.05	1.29	1.57	1.85	1.97	1.95	1.76	1.40	1.02	0.81	1.35
KV	**Average**	**0.73**	**0.84**	**1.05**	**1.32**	**1.64**	**1.97**	**2.09**	**2.07**	**1.89**	**1.45**	**1.07**	**0.81**	**1.41**

(Source: Computed from Eq.11)

Appendix 14 : Mean monthly Incoming Solar radiation (R_s) in Watt/m^2

Stn. Index	Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual mean
1007	Kakani	161.47	193.77	222.21	252.32	222.84	211.57	276.22	282.26	170.24	185.54	173.06	151.96	208.62
1015	Thankot	163.84	197.12	229.16	245.87	234.33	201.33	219.21	195.14	169.95	193.08	177.00	154.53	198.38
1021	Kirtipur[1]	164.99	198.84	231.38	249.48	239.73	204.90	201.10	186.64	180.32	198.26	176.74	155.59	199.00
1022	Godawari	161.33	196.74	229.24	255.17	245.02	201.64	212.43	192.37	174.47	195.88	175.69	152.93	199.41
1029	Khumaltar	164.23	199.15	233.54	255.02	254.05	218.70	198.58	197.24	197.66	197.78	176.68	153.53	203.85
1030	K.A.[2]	165.05	199.07	230.80	254.41	243.93	208.63	196.71	187.59	188.54	196.90	175.93	155.22	200.23
1035	Sankhu	166.34	197.19	233.63	253.80	233.55	199.89	220.85	206.29	171.79	195.94	177.37	157.33	201.17
1039	Panipokhari	164.80	199.57	229.37	243.70	247.86	208.05	196.74	186.55	188.43	196.72	174.90	155.90	199.38
1043	Nagarkot	164.10	198.75	228.21	252.62	235.12	199.38	247.88	193.64	173.75	191.32	174.94	155.29	201.25
1052	Bhakatapur	165.95	199.19	233.11	254.13	236.65	206.68	196.82	186.52	189.81	199.42	178.92	156.22	200.28
1059	Changu[3]	163.35	196.71	230.25	251.28	233.27	205.64	199.66	187.46	181.61	195.06	176.16	154.45	197.91
1060	Chapagaun	165.10	199.80	232.89	255.86	252.38	210.42	197.77	187.74	185.69	200.37	179.30	155.12	201.87
1061	Lubhu	164.99	200.97	236.58	246.25	246.98	221.37	196.72	189.23	194.84	196.60	175.94	153.14	201.97
1071	Buddha[4]	163.98	197.16	229.00	248.61	228.76	199.88	212.15	195.88	174.82	194.32	176.33	154.53	197.95
1073	Khokana	165.13	199.38	233.46	252.42	248.45	212.41	196.78	189.04	186.76	198.73	178.47	155.27	201.36
1074	Sundarijal	162.89	195.12	225.74	243.66	215.90	200.12	269.51	241.80	167.50	190.54	175.08	153.59	203.45
1075	Lele	164.37	198.96	225.12	248.08	245.14	203.89	203.55	191.54	183.01	208.70	162.76	158.85	199.50
KV	**Average**	**164.23**	**198.09**	**230.22**	**250.75**	**239.06**	**206.73**	**214.27**	**199.82**	**181.13**	**196.19**	**175.60**	**154.91**	**200.92**

([1]Bagbani, [2] Kathmandu Airport, [3] Changunarayan, [4] Buddhanilkantha)

(Source: Computed from Eq.21)

Appendix 15 : Mean monthly Net Short wave radiation (R_{ns}) in Watt / m^2

Stn Index	Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual mean
1007	Kakani	124.3	149.2	171.1	194.3	171.6	162.9	212.7	217.3	131.1	142.9	133.3	117.0	160.6
1015	Thankot	126.2	151.8	176.5	189.3	180.4	155.0	168.8	150.3	130.9	148.7	136.3	119.0	152.8
1021	Kirtipur	127.0	153.1	178.2	192.1	184.6	157.8	154.9	143.7	138.8	152.7	136.1	119.8	153.2
1022	Godawari	124.2	151.5	176.5	196.5	188.7	155.3	163.6	148.1	134.3	150.8	135.3	117.8	153.5
1029	Khumaltar	126.5	153.3	179.8	196.4	195.6	168.4	152.9	151.9	152.2	152.3	136.0	118.2	157.0
1030	Ktm Airport	127.1	153.3	177.7	195.9	187.8	160.6	151.5	144.4	145.2	151.6	135.5	119.5	154.2
1035	Sankhu	128.1	151.8	179.9	195.4	179.8	153.9	170.1	158.8	132.3	150.9	136.6	121.1	154.9
1039	Panipokhari	126.9	153.7	176.6	187.6	190.9	160.2	151.5	143.6	145.1	151.5	134.7	120.0	153.5
1043	Nagarkot	126.4	153.0	175.7	194.5	181.0	153.5	190.9	149.1	133.8	147.3	134.7	119.6	155.0
1052	Bhakatapur	127.8	153.4	179.5	195.7	182.2	159.1	151.6	143.6	146.2	153.6	137.8	120.3	154.2
1059	Changunarayan	125.8	151.5	177.3	193.5	179.6	158.3	153.7	144.3	139.8	150.2	135.6	118.9	152.4
1060	Chapagaun	127.1	153.8	179.3	197.0	194.3	162.0	152.3	144.6	143.0	154.3	138.1	119.4	155.4
1061	Lubhu	127.0	154.7	182.2	189.6	190.2	170.5	151.5	145.7	150.0	151.4	135.5	117.9	155.5
1071	Buddhanilkantha	126.3	151.8	176.3	191.4	176.1	153.9	163.4	150.8	134.6	149.6	135.8	119.0	152.4
1073	Khokana	127.1	153.5	179.8	194.4	191.3	163.6	151.5	145.6	143.8	153.0	137.4	119.6	155.0
1074	Sundarijal	125.4	150.2	173.8	187.6	166.2	154.1	207.5	186.2	129.0	146.7	134.8	118.3	156.7
1075	Lele	126.6	153.2	173.3	191.0	188.8	157.0	156.7	147.5	140.9	160.7	125.3	122.3	153.6
KV	**Average**	**126.5**	**152.5**	**177.3**	**193.1**	**184.1**	**159.2**	**165.0**	**153.9**	**139.5**	**151.1**	**135.2**	**119.3**	**154.7**

(Source: Computed from Eq.22)

Appendix 16 : Mean monthly Net Longwave radiation (R_{nl}) in Watt/m^2

Stn Index	Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual mean
1007	Kakani	81.27	80.77	78.99	79.77	59.10	52.01	81.48	91.23	47.90	72.62	86.54	82.51	74.52
1015	Thankot	83.20	83.51	83.36	78.15	65.57	48.38	57.26	51.38	48.39	77.49	89.40	84.22	70.86
1021	Kirtipur	84.73	85.39	85.09	80.22	68.31	50.07	49.24	47.51	54.00	80.90	89.54	85.49	71.71
1022	Godawari	82.31	84.27	84.12	83.05	70.66	48.53	54.25	50.15	50.83	79.32	88.77	83.57	71.65
1029	Khumaltar	84.53	85.90	86.58	83.12	74.96	56.26	48.07	52.55	63.19	80.67	89.70	84.14	74.14
1030	Ktm Airport	85.21	85.92	85.15	82.87	70.35	51.78	47.26	47.97	58.39	80.18	89.22	85.57	72.49
1035	Sankhu	85.08	83.67	85.37	81.29	64.52	47.08	57.35	56.13	48.85	78.30	88.82	86.01	71.87
1039	Panipokhari	84.98	86.21	84.36	77.63	72.16	51.51	47.26	47.47	58.32	80.08	88.48	86.08	72.05
1043	Nagarkot	81.71	82.55	80.82	79.41	63.92	45.97	67.95	49.01	48.84	73.96	85.33	82.74	70.18
1052	Bhakatapur	85.27	85.47	85.62	82.00	66.40	50.41	46.93	47.09	58.52	80.86	90.36	85.43	72.03
1059	Changunarayan	83.96	84.21	84.31	80.01	64.34	49.60	47.87	47.20	53.92	78.67	89.11	84.95	70.68
1060	Chapagaun	84.41	85.63	85.40	82.93	73.66	52.14	47.39	47.65	56.29	81.40	90.46	84.25	72.63
1061	Lubhu	84.60	86.65	87.61	78.34	71.28	57.08	46.98	48.46	61.24	79.29	88.30	83.02	72.74
1071	Buddhanilkantha	85.62	85.74	85.02	79.99	63.33	47.81	54.18	51.88	51.08	79.54	90.81	86.36	71.78
1073	Khokana	85.33	86.32	86.71	82.11	72.72	53.68	47.49	48.87	57.58	81.50	91.13	85.50	73.24
1074	Sundarijal	83.83	83.38	82.12	76.48	56.63	47.34	79.24	73.08	46.81	76.31	88.84	84.79	73.24
1075	Lele	83.46	84.64	80.86	78.91	70.10	49.08	49.82	49.26	54.67	86.14	78.13	86.79	70.99
KV	**Average**	**84.09**	**84.72**	**84.21**	**80.37**	**67.53**	**50.51**	**54.71**	**53.35**	**54.05**	**79.25**	**88.41**	**84.79**	**72.16**

(Source: Computed from Eq.23)

Appendix 17 : Mean monthly Net radiation (R_n) in Watt/m^2

Stn Index	Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual mean
1007	Kakani	43.06	68.44	92.11	114.52	112.48	110.90	131.21	126.11	83.18	70.24	46.72	34.50	86.12
1015	Thankot	42.95	68.27	93.09	111.17	114.86	106.65	111.53	98.87	82.47	71.19	46.89	34.77	81.89
1021	Kirtipur[1]	42.31	67.72	93.07	111.88	116.29	107.70	105.61	96.20	84.84	71.77	46.55	34.31	81.52
1022	Godawari	41.91	67.22	92.40	113.43	118.00	106.73	109.32	97.98	83.51	71.51	46.52	34.18	81.89
1029	Khumaltar	41.93	67.45	93.24	113.24	120.66	112.13	104.83	99.32	89.01	71.62	46.34	34.07	82.82
1030	K.A.[2]	41.88	67.36	92.56	113.02	117.48	108.87	104.21	96.47	86.78	71.43	46.24	33.95	81.69
1035	Sankhu	43.00	68.17	94.53	114.14	115.31	106.83	112.70	102.71	83.43	72.57	47.76	35.14	83.02
1039	Panipokhari	41.92	67.46	92.26	110.01	118.70	108.69	104.23	96.18	86.77	71.40	46.20	33.95	81.48
1043	Nagarkot	44.64	70.49	94.90	115.10	117.12	107.55	122.92	100.09	84.95	73.36	49.37	36.84	84.78
1052	Bhakatapur	42.52	67.91	93.87	113.68	115.81	108.73	104.62	96.53	87.63	72.69	47.41	34.86	82.19
1059	Changu[3]	41.82	67.26	92.98	113.48	115.28	108.74	105.87	97.14	85.92	71.52	46.53	33.98	81.71
1060	Chapagaun	42.72	68.22	93.92	114.08	120.68	109.88	104.89	96.91	86.69	72.88	47.59	35.19	82.80
1061	Lubhu	42.44	68.10	94.56	111.27	118.90	113.38	104.49	97.25	88.78	72.10	47.17	34.90	82.78
1071	Buddha[4]	40.64	66.07	91.31	111.44	112.82	106.10	109.17	98.94	83.53	70.08	44.97	32.64	80.64
1073	Khokana	41.82	67.20	93.05	112.26	118.59	109.88	104.03	96.69	86.22	71.52	46.29	34.06	81.80
1074	Sundarijal	41.59	66.86	91.70	111.13	109.61	106.75	128.28	113.10	82.16	70.41	45.97	33.48	83.42
1075	Lele	43.11	68.56	92.48	112.11	118.66	107.91	106.92	98.23	86.24	74.55	47.20	35.53	82.62
KV	**Average**	**42.37**	**67.81**	**93.06**	**112.70**	**116.54**	**108.67**	**110.28**	**100.51**	**85.42**	**71.81**	**46.81**	**34.49**	**82.54**

([1]Bagbani, [2] Kathmandu Airport, [3] Changunarayan, [4] Buddhanilkantha)

(Source: Computed from Eq.19)

Appendix 18 : Constants for the Wind Model

Month	A	A_1 (x 10^{-2})	A_2 (x 10^{-5})	R^2
Jan	48.065	-5.00	6.0	0.95
Feb	63.517	-4.89	6.0	0.96
Mar	81.228	-3.87	6.0	0.93
Apr	110.14	-5.33	6.0	0.87
May	123.06	-8.56	7.0	0.85
Jun	120.53	-14.33	10.0	0.91
Jul	107.02	-15.72	10.0	0.93
Aug	93.747	-14.44	10.0	0.95
Sep	71.655	-10.44	8.0	0.96
Oct	45.37	-4.92	6.0	0.96
Nov	39.642	-4.48	6.0	0.97
Dec	41.476	-4.63	6.0	0.97

(Source: Pokhrel 1998)

Appendix 19 : Recorded Wind speed at 2 m in m/s

Stn Index	Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1007	Kakani	1.50	1.77	2.06	1.93	2.10	1.53	1.49	1.39	1.13	1.15	1.04	1.13
1029	Khumaltar	0.94	1.18	1.30	1.31	1.33	1.29	1.29	1.11	1.10	1.01	0.89	0.82
1030	Kath Airport	0.58	0.79	1.03	1.16	1.12	0.95	0.88	0.69	0.61	0.43	0.41	0.36
1043	Nagarkot	2.21	2.71	3.24	2.96	2.95	2.53	2.12	1.89	2.08	1.91	1.87	1.94

(Source: DHM, 1976-1986)

Appendix 20 : Class A Pan Evaporation in mm/day recorded at three stations

Stn Index	Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1007	Kakani	1.96	2.49	3.72	4.37	3.34	2.59	2.62	2.35	2.20	2.89	2.22	2.03
1029	Khumaltar	1.72	2.56	3.80	4.38	4.44	4.53	4.07	4.21	3.56	3.06	2.22	1.65
1030	KTM Airport	1.71	2.40	3.44	4.11	4.46	3.49	3.32	2.89	3.03	2.77	2.06	1.28
KV	**Average**	**1.79**	**2.48**	**3.65**	**4.29**	**4.08**	**3.53**	**3.34**	**3.15**	**2.93**	**2.91**	**2.17**	**1.66**

(Source: DHM, 1976-1986)

Appendix 21 : Rainfall and Evapotranspiration of Kathmandu Airport

month	monthly rainfall		evapotranspiration	
	mm/month	rel. % of year	mm/day	mm/month
1	14	1.0	1.8	54
2	16	1.1	2.7	81
3	31	2.2	4.1	123
4	55	3.9	5.0	150
5	103	7.3	5.5	165
6	243	17.2	4.8	144
7	369	26.1	4.4	132
8	296	20.9	4.1	123
9	203	14.4	3.8	114
10	63	4.5	3.3	99
11	7	0.5	2.3	69
12	13	0.9	1.7	51
SUM	**1413**	-	-	**1305**

(source: DHM, Kathmandu Airport, 1968-1980)