Evapotranspiration is combined loss of water from soil as well as plants and it is also a crucial component of Hydrologic Cycle. But at the same time ET depends upon several factors and it is very difficult to calculate it precisely. Existing methods including empirical as well as experimental methods provide ET results for homogeneous areas. As stated in chapter 1, the present study aims to estimate evapotranspiration spatially by Surface Energy Balance model using satellite data and to generate spatial ET maps of wheat crop after validation. In this chapter, the entire literature review portion is divided into different sections depending upon various components involved in the ET estimation. These section are (2.1) Evapotranspiration (2.2) Empirical Models to estimate Evapotranspiration (2.3) Surface Energy Balance Models (2.4) Experimental methods to measure evapotranspiration.

2.1 Evapotranspiration

It is the combination of two separate processes through which, water is lost from the soil surface via evaporation process and from the crop by transpiration. (Allen, 1998) [27].

2.1.1 Reference crop evapotranspiration (ETo)

It represents the rate of evapotranspiration from an extensive surface of 8 to 15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water [35]. The methodology to compute ETo is suggested by Allen (1989) [36]. Lee et al (2004) [28] found that computation of monthly average evapotranspiration with eight evapotranspiration estimation methods (Penman, Penman-Monteith, Pan Evaporation, Kimberly-Penman, Priestley- Taylor, Hargreaves, Samani-Hargreaves and Blaney-Criddle) have the same trend throughout the year.
2.1.2 Crop coefficient

Crop coefficient \( K_c \) is the ratio of potential evapotranspiration for a given crop to the evapotranspiration of a reference crop. It represents an integration of effects of four primary characteristics that adjusts the crop from reference grass (i) Crop height, (ii) Albedo, (iii) Canopy resistance, (iv) Evaporation from soil; especially exposed soil. Factors determining the crop coefficient are crop type, climate, soil moisture evaporation, crop growth stage [27].

2.1.3 Crop evapotranspiration, \( ET_c \)

It is the evapotranspiration from disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions and achieving full production under the given climatic conditions.

2.1.4 Actual Evapotranspiration

The amount of water that evaporates from the surface and is transpired by plants, if the total amount of water is limited, then it means actual combined loss of water from plants and soil.

2.1.5 Potential Evapotranspiration

The amount of water that would evaporate from the surface and be transpired by plants, when the supply of water is unlimited.

2.1.6 Wheat Crop and Phenology

India is the fourth largest producer of wheat crop in the world. Wheat is an important cereal crop grown in India and it is cultivated in almost all parts of country. Geographically, India has been divided into six wheat growing zones. Wheat is a rabi crop which is sown in the beginning of winter (November-December) and is harvested in the beginning of summer. Haryana contributes about 13.3% towards national production of wheat from the 8.9% of wheat growing area of the country, with an average productivity of nearly 4 tonnes/ha. The area, production and productivity, averaged over last five years are 2.3 million ha, 9.3 tonnes and 4 tonnes/ha respectively. The trend during last five years has shown marginal decline in production and productivity in nearly stable areas of cultivation. Wheat production
in Haryana state is not increasing due to continuous depleting water table, reduced soil organic carbon status, nutrient mining, imbalanced fertilization, crop residue burning leading to nutrient and organic carbon loss etc. Wheat crop has various growth stages and wheat phenology [38] is shown in Figure 2.1.

Figure 2.1 Growth stages of wheat crop [37]

2.2 Evapotranspiration by Empirical Models

Various empirical models for estimation of evapotranspiration are available. Blaney-Criddle (BC) 1942, Penman-Monteith FAO 56 (PM) 1998, ASCE standardized Penman-Montieth (ASCE) 2005, Priestley Taylor 1972, Thornthwaite (TW) 1948 and Hargreaves-Samani (HS)1985 [38, Subedi] are the most commonly used empirical models. These empirical models are explained here also. Advantages, limitations and application time step of different ET estimation models are also presented in Table 2.1 to 2.4.

2.2.1 Blaney-Criddle Method

The Blaney-Criddle method was first developed in 1942. It is an empirical equation and very simple to use. They developed a simple mathematical model [39] as given by “Equation” (2.1)

\[ u = kf \] (2.1)
Where \( u \) = monthly consumptive use, in inches

\( f = TF \times p / 100 \) is the monthly consumptive use factor

\( TF = \) mean monthly temperature, in degrees Fahrenheit (°F)

\( p = \) monthly percentage of daytime hours of the year

\( k = \) empirical consumptive use crop coefficient for monthly period

### 2.2.2 Thornthwaite Method (1948)

In 1948, Thornthwaite and Penman both developed potential evapotranspiration equation independently[40]. Potential ET here refers to the maximum ET that can occur from a given crop surface. Penman’s equation was more mechanistic while Thornthwaite’s equation was more empirical.

\[
PET = 16 \left( \frac{10Ta}{I} \right)^\alpha \tag{2.2}
\]

Where \( PET = \) potential evapotranspiration rate, in mm per month

\( Ta = \) mean monthly air temperature, in degrees Celsius (°C)

\( I = \) summation of the 12 monthly heat index \( i \), where \( i = (Ta / 5)1.514 \)

\( \alpha = \) an empirical coefficient

### 2.2.3 Hargreaves (1975) (for deg. F)

Hargreaves (1975) developed an equation for estimating ET which doesn’t require wind speed data[41]. His equation was as follows:

\[
ET_o = 0.0075RsT_F \tag{2.3}
\]

Where \( ET_o = \) potential ET for a grass reference surface in the same units as \( Rs \)

\( Rs = \) global solar radiation at the surface in equivalent water evaporation, usually mm of evaporation

\( TF = \) mean air temperature in degrees Fahrenheit (°F).
2.2.4 **Hargreaves-Samani (1985), (deg. C)**

Hargreaves and Samani (1982) developed an equation to determine $R_s$ from extraterrestrial radiation ($Ra$) and the air temperature range ($TD$)

$$ET_0 = 0.0022R_s(T_a + 17.8)TD^{0.5}$$  \hspace{1cm} (2.4)

$Ra= extraterrestrial\ radiation, \ MJ/m^2/d\ or\ MJ/m^2/h.$

$Ta=mean\ monthly/daily/hourly\ air\ temperature, \ ^\circ C$

$TD= mean\ maximum\ minus\ mean\ minimum\ temperature, \ ^\circ C$

2.2.5 **Christiansen (1968)**

Christiansen (1968) developed a simple method to estimate pan evaporation and crop evapotranspiration[43]. According to Christiansen, the reasons for using pan evaporation data were: they were more consistent, already considerable work had been done to relate pan evaporation data with crop consumptive use and the pan evaporation data were readily available. The mathematical model that he developed was as follows:

$$E = KR_aC$$  \hspace{1cm} (2.5)

$E$ is used in a general sense to apply to evaporation or evapotranspiration

$K$ is a dimensionless constant developed empirically from data analysis

$C$ is a dimensionless coefficient related to climatic parameters

$Ra$ is the extraterrestrial radiation, expressed as equivalent depth of evaporation

2.2.6 **Original Penman Equation (1948)**

Penman (1948) developed a mechanistic approach to calculate $ET$[44]. He used a combination approach by combining the surface energy balance equation with an aerodynamic equation.

$$ET = \frac{(\Delta R_n - \Delta G) + k_w(e_v - e_a) f(u)\gamma}{\bar{\lambda}(\Delta + \gamma)}$$  \hspace{1cm} (2.6)

$$f(u) = a_w + b_w u_2$$  \hspace{1cm} (2.7)

$ET0 = grass\ reference\ ET\ (mm/d);$
Rn = net radiation at the crop surface (MJ/m²/d);

G = soil heat flux density (MJ/m²/d).

f(u) = wind speed function

kw = unit coefficient (6.43 for ET in mm/d or 0.268 for ET in mm/h)

ea=actual vapor pressure, kPa.

Es=saturation vapor pressure, kPa.

Δ=slope of saturation vapor pressure with air temperature, kPa/°C.

γ= psychrometric constant, kPa/°C.

Λ=latent heat of evaporation, MJ/kg.

2.2.7 CIMIS Penman Method

The CIMIS Penman method uses equation 2.6 by incorporating following values of aₚₚ and bₚₚ[35]

aₚₚ = 0.29 and bₚₚ = 0.53 for Rn > 0 and aₚₚ = 1.14 and bₚₚ = 0.40 for Rn ≤ 0.(2.8)

2.2.8 Penman Monteith (1965)

Monteith (1965) introduced some crop resistance terms in the original Penman equation and the equation later came the well-known “Penman-Monteith” (PM) ET equation[45]. This equation is explained in detail in chapter 3.

\[ \lambda E = \frac{\Delta(R_n - G) + \rho_ac_p(\varepsilon_a - \varepsilon_r)}{\Delta + \gamma(1 + \frac{\Delta_c}{r_a})} \]  

(2.9)

2.2.9 Priestley Taylor (1972)

Priestley and Taylor (1972) developed a semi-empirical equation[46] to calculate potential evaporation (λE or ET), which is applicable for partial equilibrium condition. Their equation is as follows

\[ \lambda E = \alpha \Delta(R_n - G)/(\Delta + \gamma) \]  

(2.10)

where \( \alpha = 1.26 \) for water surfaces with minimum advection
2.2.10 FAO 56 Penman-Monteith Equation

The FAO 56 PM equation was based on the Penman-Monteith equation. The FAO 56 PM method defines the reference crop as a hypothetical crop with an assumed height of 0.12 m having a surface resistance of 70 s/m and an albedo of 0.23, closely resembling the evaporation of an extensive surface of green grass of uniform height, actively growing and adequately watered. This equation is used in present study to estimate reference evapotranspiration[27]and also explained in detail in chapter 3.

\[
ET_o = \frac{0.408\Delta(R_n-G)+\gamma 9000}{\Delta+y(1+0.34u_2)}
\]

(2.11)

2.2.11 ASCE-EWRI Standardized Penman Monteith Evapotranspiration Equation

The ASCE Standardized Reference Evapotranspiration Equation (ASCE EWRI, 2005)[47] is based on the Penman-Monteith equation, with some simplification and standardization on the aerodynamic and surface resistances.

\[
ET_{ss} = \frac{0.408\Delta(R_n-G)+\gamma C_n u_{273}}{\Delta+y(1+C_d u_2)}
\]

(2.12)

Cn: numerator constant that changes with reference type and calculation time step, K mm s\(^3\) M/g/d or K mm s\(^3\)M/g/h.

Cd: denominator constant that changes with reference type and calculation time step, s/m.

2.2.12 Valiantzas Model (2006, 2013)

Valiantzas (2006) developed a set of equations to determine the ET\(_o\) rate based on simplifications made to the Penman (1963) equation. His purpose was to enable ET computation[48-49] with limited meteorological data.

\[
ET_o \approx 0.0393 R_S \sqrt{T_a + 9.5} - 0.19 R_s^{0.6} \phi^{0.15} + 0.048(T_a + 20) \left(1 - \frac{RH}{100}\right) u_2^{0.7}
\]

(2.13)

\(\phi\) is the latitude of the site (radians),

RH is the relative humidity (%)
2.2.13 Katerji and Perrier (KP) model (1983)

Katerji and Perrier (1983) found that a linear relationship can be established between the two ratios rc/ra and r*/ra, where r* is a climatic resistance term[50]. They developed the following empirical relation

\[
\frac{r_c}{r_a} = a \frac{r^*}{r_a} + b \quad (2.14)
\]

\[
r^* = \frac{\Delta + \gamma \rho C_p D}{\Delta \gamma R_n + \gamma} \quad (2.15)
\]

where r* is a climatic resistance term

Where a and b are empirical calibration coefficients

rc: canopy surface resistance, s/m.

ra: aerodynamic resistance, s/m.

\(\rho\): air density, kg/m\(^3\).

2.2.14 Todorovic Model (1999)

Todorovic (1999) presented a mechanistic approach to calculate surface resistance using weather variables[51]. His summarized methodology is as follows

\[
t = \frac{\gamma D}{\Delta (\gamma + \Delta)} \quad (2.16)
\]

t = the difference between actual canopy temperature and canopy temperature (°C) in wet conditions

D: vapor pressure deficit, kPa

2.2.15 Li et al. Model (2009)

Li et al. (2009) found some errors in the Todorovic model in the derivation of “t”. Li et al. (2009) derived “t” as

\[
t = \frac{Y D C}{\Delta (\Delta + \gamma)} \quad (2.17)
\]

Li et al. proved[52] that Todorovic’s method missed the term C while deriving “t”. The missing parameter C was described as shown in Equation
\[ C = \frac{\left( \frac{1}{T} \right) \left( \frac{1}{r} \right)}{\left( 1 + \frac{1}{r} \right) \left( \frac{1}{T} \right) + \left( \frac{1}{r} \right)} \]  
\hspace{10cm} (2.18)

Table 2.1 Advantages, limitations and application time step of different ET estimation models

<table>
<thead>
<tr>
<th>S. No</th>
<th>Methods</th>
<th>Advantages</th>
<th>Limitations</th>
<th>Application Timestep</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Blaney-Criddle Method (1942)</td>
<td>Simplicity ET</td>
<td>Underestimation in general</td>
<td>Monthly</td>
</tr>
<tr>
<td>2</td>
<td>Thornthwaite Method (1948)</td>
<td>Simplicity ET</td>
<td>Underestimation in advective condition</td>
<td>Monthly</td>
</tr>
<tr>
<td>3</td>
<td>Hargreaves and Samani (1985)</td>
<td>Simplicity</td>
<td>Problems of over and under estimation of ET</td>
<td>Weekly</td>
</tr>
<tr>
<td>4</td>
<td>Christiansen Method (1968)</td>
<td>More or less accurate to predict ET for monthly timestep</td>
<td>Not accurate to calculate ET for daily or shorter timesteps</td>
<td>Monthly</td>
</tr>
</tbody>
</table>

Table 2.2 Advantages, limitations and application time step of different Empirical models

<table>
<thead>
<tr>
<th>S. No</th>
<th>Methods</th>
<th>Advantages</th>
<th>Limitations</th>
<th>Application Timestep</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Original Penman Equation (1948)</td>
<td>Physical equation based on the combination of surface energy balance equation and aerodynamic equation</td>
<td>Wind speed function is difficult to obtain. The equation was mainly developed for evaporation from free water surfaces.</td>
<td>Daily, hourly</td>
</tr>
<tr>
<td>2</td>
<td>CIMIS Penman Method</td>
<td>( a_w ) and ( b_w ) coefficients used in ( f(u) ) are easy to obtain. Also applicable for hourly timesteps.</td>
<td>The coefficients used in this equation were developed for Californian condition, hence it may not be applicable</td>
<td>Hourly</td>
</tr>
</tbody>
</table>
Penman Monteith equation (1965)  | Physical equation with the inclusion of rc. | It is difficult to directly implement this equation to calculate actual crop ET, as rc is difficult to obtain. | Daily, hourly |
--- | --- | --- | --- |


### Table 2.3 Advantages, limitations and application time step of different Fixed Surface Resistance Approach related models

<table>
<thead>
<tr>
<th>S. No</th>
<th>Methods</th>
<th>Advantages</th>
<th>Limitations</th>
<th>Application Timestep</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>FAO 56 PM Equation (1998)</td>
<td>Considered very accurate to calculate grass reference ET on daily basis</td>
<td>May not be applicable to apply for hourly timestep.</td>
<td>Daily</td>
</tr>
<tr>
<td>2</td>
<td>ASCE-EWRI Standardized PM Equation (2005)</td>
<td>It can calculate both grass and Alfalfa reference crop ET on both hourly and daily timesteps.</td>
<td>Kc needs to be developed also for alfalfa reference surfaces. The use of fixed rc for entire day may induce some errors in estimating reference ET.</td>
<td>Daily, hourly</td>
</tr>
<tr>
<td>3</td>
<td>Valiantzas Model (2006, 2013)</td>
<td>Relatively simple, can be used when some parameters like wind speed is missing.</td>
<td>It is semi-empirical, so may not be accurate enough as PM equation.</td>
<td>Daily</td>
</tr>
</tbody>
</table>
Table 2.4 Advantages, limitations and application time step of different Variable Surface Resistance Approach related models

<table>
<thead>
<tr>
<th>S. No</th>
<th>Methods</th>
<th>Advantages</th>
<th>Limitations</th>
<th>Application Timestep</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Jarvis Model (1976)</td>
<td>New concept to calculate stomatal resistance</td>
<td>It is not easy to obtain canopy resistance (rc) from stomatal resistance.</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Katerji-Perrier Model (1983)</td>
<td>Relatively simple to calculate actual crop ET in one step process.</td>
<td>This is empirical method. The coefficients “a” and “b” need to be tested for different species and also for different climatic conditions.</td>
<td>Daily, hourly</td>
</tr>
<tr>
<td>3</td>
<td>Todorovic Model (1999)</td>
<td>Mechanistic equation to calculate rc</td>
<td>Some flaws in the procedure as shown by Li et al. (2009)</td>
<td>Hourly</td>
</tr>
<tr>
<td>4</td>
<td>Li et al. Model (2009)</td>
<td>Relatively simple to Implement</td>
<td>Only applicable for winter wheat crop in North China Plain</td>
<td>Hourly</td>
</tr>
<tr>
<td>5</td>
<td>Shuttleworth Model (2006, 2009)</td>
<td>Provides one step ET for daily timestep based by calculating rc based on Kc.</td>
<td>Complicated to use, rc is a function of FAO-56 Kc values, in other words rc depends on the accuracy of Kc.</td>
<td>Daily</td>
</tr>
</tbody>
</table>
Penman-Montieth method is considered as standard method and approved by FAO, thus various scientists have validated the outcome of their research work and adopted PM method, for ET estimation.

In Changins Station at Switzerland[53] ET was calculated by five empirical methods namely Hargreaves and Blaney-Criddle (temperature-based), Makkink and Priestley-Taylor (radiation-based) and Rohwer (mass-transfer-based), took Penman-Monteith method, recommended by FAO-56 [27] as a standard method for evaluating the other standard method.

In Naein city, Isfahan province (center of Iran) from 1993-2006 [54], evapotranspiration (ET) was determined using several models and their results were compared with FAO Penman Monteith (FAO-56 PM) method. Results showed that Blaney-Criddle (BC) model was the best in light of mean biased error (MBE), root mean square error (RMSE) and maximum absolute error (MAXE). The mean values of MBE, RMSE and MAXE were computed -0.554, 0.690 and 1.429 mm/d, respectively.

In Policoro of southern Italy, daily values of evapotranspiration [Trajkovic, 2010] [55] were estimated by FAO-56 Penman-Monteith (FAOPM), FAO-24 Penman (FAOPn), FAO-24, Blaney-Criddle (FAOBC), FAO-24 Radiation (FAOR), FAO-24 Pan, Priestley-Taylor (PT) and Hargreaves (HARG) methods. The results strongly support the use of the FAO-24 Pan and FAO-56 Penman-Monteith equations for the calculation of daily reference evapotranspiration.

In Uberaba, state of Minas Gerais, Brazil [56], evaluation of various empirical methods to estimate evapotranspiration viz Blaney-Criddle, Jensen-Haise, Linacre, Solar Radiation, Hargreaves-Samani, Makkink, Thornthwaite, Camargo, Priestley-Taylor and Original Penman for 21 years (1990-2010) was done and results were compared with Penman-Monteith standard method (FAO56). They concluded that the Makkink and Camargo methods showed the best performance and the Hargreaves-Samani method presented a better linear relation with the standard method, with a correlation coefficient (r) of 0.88.

In Mediterranean climate, simple forms of Penman equations that were recently developed were used [57]. The new empirical equations were applied to
daily climatic data from four stations located in the Mediterranean region of Turkey viz Adana, Antalya, Isparta, and Mersin. The results were compared with the ETo values obtained by Food and Agricultural Organization-56 Penman-Monteith method and the other empirical equations viz Copais, Turc, Hargreaves-Samani, Hargreaves, Ritchie, and Irmak. Root mean square error, mean absolute errors, and determination coefficient statistics were used for comparison of the empirical models. The results indicated that the Valiantzas equation with full weather data performs better than the other empirical methods at stations in Adana, Antalya, and Isparta. In the Mersin station, however, the Copais equation performed the best out of the nine methods. The worst estimates were generally obtained from the Turc method.

At Campos dos Goytacazes region, in Rio de Janeiro state [58], study of evaluating six empirical methods to estimate evapotranspiration was conducted in contrast to FAO56-Penman-Monteith equation. The results indicated that the differences observed between the values obtained using the empirical models applied in this study and the values calculated by the FAO56-Penman-Monteith equation were greater than 10%, which means an error of about 0.5 mm.day\(^{-1}\). After summarising all the empirical methods, it can be concluded that FAO Penman Monteith -56 method is most accurate and it is declared as a standard method by FAO. In the present study same method was adopted for the monthly ET analysis of the study area and as a one of the validation method.

2.3 **Surface Energy Balance Models:**

Remote sensing based energy balance algorithms convert satellite sensed radiances into land surface characteristics such as albedo, leaf area index, vegetation indices, surface roughness, surface emissivity, and surface temperature to estimate ET as a residual of the land surface energy\[59\] balance equation

\[
ET = R_n - H - G_o
\]

(2.19)

where ET is the latent heat flux (evapotranspiration) associated with evaporation of water from soil and water from vegetation, \(R_n\) is the net radiation absorbed at the land surface, H is the sensible heat flux to warm or cool the atmosphere, and \(G_o\) is the soil heat flux to warm or cool the soil, all expressed in (Wm\(^{-2}\)). Majority of the
Energy Balance models differ mainly in the manner in which H is estimated. Some energy balance models are listed in table 2.6[60] with their main inputs, assumptions, advantages and disadvantages.

Table 2.5 Comparisons of the different remote sensing ET models

<table>
<thead>
<tr>
<th>S. No</th>
<th>Methods</th>
<th>Assumptions</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Simplified</td>
<td>1) Daily soil heat flux is negligible; 2) Instantaneous H at mid day can express the influence of partitioning daily available energy into turbulent fluxes.</td>
<td>Simplicity</td>
<td>Site-specific</td>
</tr>
<tr>
<td></td>
<td>Equation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>$VI-T_s$ Triangle</td>
<td>1) Complete range of both soil moisture and vegetation coverage exists within the study area at satellite pixel scale 2) Cloud contaminations are discarded and atmospheric effects are removed 3) $EF$ varies linearly with $T_s$ for a given $VI$</td>
<td>No ground based measurements are needed</td>
<td>1) Difficult to determine the dry and wet edges 2) $VI-T_s$ triangle form is not easy recognized with coarse spatial resolution data</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>$VI-T_s$ Trapezoid</td>
<td>1) Dry and wet edges are linear lines and vary linearly with $VI$ 2) $EF$ varies linearly with $T_s$ for a given $VI$.</td>
<td>Whole range of $VI$ and soil moisture in the scene of interest is not required</td>
<td>1) Uncertainty in the determination of dry and wet edges 2) A lot of ground based measurements are needed.</td>
</tr>
<tr>
<td></td>
<td>Method</td>
<td>Characteristics</td>
<td>Remarks</td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>--------</td>
<td>----------------</td>
<td>---------</td>
<td></td>
</tr>
</tbody>
</table>
| 4 | SEBI   | 1) Dry limit has a zero surface ET  
2) Wet limit evaporates Potentially | Directly relating the effects of $Ts$ and $ra$ on $LE$.  
Ground-based measurements are needed. |
| 5 | SEBAL  | 1) Linear relationship between $Ts$ and $dT$;  
2) ET of the driest pixel is 0  
3) $ET_{wet}$ is set to the surface available energy. | 1) Minimum ground measurements  
2) Automatic internal calibration;  
3) Accurate atmospheric corrections are not needed  
1) Applied over flat surfaces  
2) Uncertainty in the determination of anchor pixels. |
| 6 | S-SEBI | 1) EF varies linearly with $Ts$ for a given surface albedo.  
2) $T_{\text{max}}$ corresponds to the minimum LE.  
3) $Ts$, min corresponds to the maximum LE. | No ground-based measurements are needed  
Extreme temperatures have to be location specific. |
| 7 | SEBS   | 1) At the dry limit, ET is set to 0  
2) At the wet limit, ET takes place at potential rate | 1) Uncertainty in SEBS from $Ts$ and meteorological variables can be limited and reduced;  
2) Computing explicitly the roughness height for heat transfer instead of using fixed values.  
1) Too many parameters are required  
2) Solution of the turbulent heat fluxes is relatively complex. |
| 8 | METRIC | 1) For the hot pixel, ET is equal to zero  
2) For the wet pixel, $LE$ is set to $1.05ETr$. | Same as SEBAL but surface slope and aspect can be considered.  
Uncertainty in the determination of anchor pixels |
|   | TSM       | 1) Fluxes of soil surfaces are in parallel or in series with fluxes of canopy leaves  
2) Priestly-Taylor Equation is employed to give the first guess of canopy transpiration | 1) Effects of view geometry are taken into account  
2) Empirical corrections for the ‘excess resistance’ are not needed | 1) Many ground measurements are needed.  
2) Component temperatures of soil and vegetation are required. |
<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>TSTIM/ALEXI</td>
<td>Surface temperature changes linearly with the time during the morning hours of the sensible heating</td>
<td>Errors due to atmospheric corrections and surface emissivity specification are significantly reduced</td>
</tr>
</tbody>
</table>

As discussed above there are several remote sensing models and have different input parameters as well as advantages and disadvantages. In the present study, Surface Energy Balance Algorithm for Land (SEBAL) has been used to estimate Evapotranspiration. SEBAL model is mainly developed for flat terrain and it has also added advantages of internal calibration. The study area is also flat terrain, thus SEBAL model is most suitable to estimate evapotranspiration. Many scientists estimated evapotranspiration using SEBAL model and suggested to develop more validation techniques for different agroclimatic zones, so that SEBAL model can be used on real time basis for water management and for policy making. Some studies related with the estimation of evapotranspiration by SEBAL as well as other remote sensing models are mentioned below:

SEBAL and METRIC are accepted in western US because of their internalised procedures, [61]. They also tested and compared these remote sensing algorithms in southern US. The evapotranspiration maps created by METRIC and SEBAL have been tested against lysimeter data and eddy covariance measurements, which shows good consistency and agreement for irrigated fields. They also concluded that SEBAL can also be applied without using any ground measurements, while METRIC needs at least one high quality weather station data on the ground to calculate the reference ET. Thus, the former algorithm would be the method of
choice in regions of the world that have no ground weather data or where high quality weather data are not available. The latter algorithm is applied where high quality ground meteorological measurements are available on an hourly basis.

In cotton experimental field [62] of EMBRAPA (EmpresaBrasileira de PesquisaAgropecuária) Bowen ratio measurements were to obtain the energy balance components. SEBAL and S-SEBI algorithms were used with four TM Landsat – 5 images of 2005, in order to determine the actual evapotranspiration of cotton crop. The comparison between the estimated values by remote sensing algorithms and field observations showed the satisfactory accuracy of the methods with mean absolute difference between SEBAL and Bowen ratio of 0.30 mm day$^{-1}$ and between S-SEBI and Bowen ratio of 0.48 mm day$^{-1}$. It can also be concluded from the study that the SEBAL algorithm performance has been better than S-SEBI algorithm.

In Mahidasht, Kermanshah province, Iran [63] ET was estimated by satellite based SEBAL and SEBS models using LANDSAT TM images and compared with Lysimeter data of same region and found that both models performed good with reasonable accuracy.

In farming areas of Maiamei rural district in Mashhad, Iran[64], evapotranspiration was estimated by SEBAL model and energy components from this model were studied. By conducting research on the treatment of this method on different vegetations, it was concluded that the modified simple form of SEBAL model can also be developed.

In Nansi Lake Wetland, China[65], the pixel-scaled actual evapotranspiration estimation was conducted via SEBAL using Landsat-7 ETM+ images, DEM and meteorological data. This data compared with the recorded pan evaporation, the estimated evapotranspiration calculated by SEBAL agreed well with the results derived from pan observations. They also studied the spatial distribution characteristic of daily evapotranspiration, which was analyzed by referencing the land-use map.

In Southeastern Colorado, a semi-arid area [66] where advection effects are large, SEBAL-Advection or SEBAL-A which is a remote sensing ET algorithm that
accounts for advection with limited data, is developed and validated using Lysimeter data.

At Blue Nile regions of Sudan [67], regional evapotranspiration was estimated by three models viz Thornthwaite water balance method (WB), complementary relationship method (GG) and SEBAL method, results of these methods were compared and found SEBAL model was better among all methods.

In Denmark, evapotranspiration rates were estimated by using standard meteorological field data and radiometric surface temperature recorded for bare soil, maize and wheat canopies [17]. They have used three unknown parameters i.e the atmospheric resistance ($r_a$), the surface resistance ($r_s$) and the vapour pressure at the surface ($e_s$). The estimated LE is compared to latent heat fluxes and fluxes recorded by the eddy covariance technique.

In the Pampa region of Argentina, estimation of evapotranspiration was done by using NOAA AVHRR imagery. They used Advanced Very High Resolution Radiometer (AVHRR) sensor on board on National Oceanic and Atmospheric Administration (NOAA) satellite [68] images and estimated evapotranspiration by using normalized difference vegetation index and compared with the water balance technique using multiple regression analysis. The relationship between spectral data and ET was more sensitive to the dates than to the sites used to generate the models.

In Middle Rio Grande, Upper San Pedro River and Lower Colorado River evapotranspiration was estimated using Enhanced Vegetation Index by MODIS and from eddy covariance and Bowen ratio flux towers [69]. ET measured from nine flux towers (eddy covariance and Bowen ratio) was strongly correlated with Enhanced Vegetation Index (EVI) values. The correlation coefficient between ET from EVI and tower sites was found to be 0.74. ET rates estimated from the flux towers and by remote sensing in this study were much lower than values estimated for riparian water budgets using crop coefficient methods.

A Remote Sensing based algorithm, ETMA (high-resolution evapotranspiration mapping algorithm) was applied to riparian meadow restoration sites [70]. This algorithm requires only local weather-station data, including the ground heat flux and high resolution airborne thermal imagery. Two parameters $T_{\text{latent}}$ and $T_{\text{sensible}}$ are defined as the surface temperatures at which all of the turbulent
heat flux is accounted for the latent and sensible heat fluxes, respectively. These points are used to develop linear relationships between surface temperature and ET at specified times.

In Central Asia two methods were used to estimate the crop evapotranspiration (ET) [71]. In the first ET was estimated by Penman Monteith method, through satellite data, crops were identified and evaporative water demands were calculated and in the second method modified SEBAL approach was used to estimate evapotranspiration. Close agreement was found between both the methods.

In Saskatchewan, Canada a distributed hydrological model for mapping evapotranspiration using remote sensing data was carried out. Spatial and temporal variation patterns of evapotranspiration (ET) was also mapped by hydrological model [72]. In this model meteorological, topographical and soil data was also used in addition to LANDSAT TM data to map vegetation types and Leaf Area Index (LAI). Simulated ET was compared with eddy-covariance ET measurements and was found close agreement between them.

In Roxo, Portugal by using Remote Sensing and GIS tools Catchment water balance was assessed. This area suffers from high level of water scarcity [73]. The most crucial component for the catchment water balance study is actual evapotranspiration, which was derived on pixels by pixel basis from MODIS, and Landsat TM and ETM+ images acquired within the study period by employing Surface Energy Balance Algorithm for Land (SEBAL).

At Hebei Plain in Northeastern China, the evapotranspiration was estimated by Surface Energy Balance System (SEBS) model using MODIS/TERRA images [74], in combination of meteorological data collected in meteorological stations distributed over the study area. The results were compared with large weighing lysimeter ET in Luancheng Agro- Ecosystem Station (LAES) located near Shijiazhuang city. Comparison showed good agreement. Model of SEBS was also used to analysis the soil moisture status of the study area from cloud free images.

In Hupselse Beek, in the Netherlands estimation of spatial and temporal distribution of evapotranspiration by satellite remote sensing was estimated [75]. He compared remote sensing Evapotranspiration with conventional ground based
methods viz Penman-Monteith method and Makkink equation. The ground truthing of study area was also done. The broad band albedo, surface temperature and broad band emissivity were estimated using pre-processed satellite data. Two surface energy Balance models SEBAL & S-SEBI were applied to estimate actual evapotranspiration. The actual ET estimates from SEBAL and S-SEBI were also in close agreement with each other, both spatially as well as temporally. The scintillation method also exhibited comparable results with actual ET estimated by both the energy balance models.

SEBAL (Surface Energy Balance Algorithm for Land) and METRIC (Mapping Evapotranspiration at high Resolution with Internalized Calibration) are satellite-based image-processing models [76] which were analysed in detail and study concluded that both SEBAL and METRIC has their own advantages and disadvantages. Both models use near surface temperature gradient in the context of surface temperature, which eliminates the requirement of accurate surface temperature and air temperature. METRIC has its own major advantage that it considers as slope and aspect functions. The SEBAL and METRIC models represent a maturing technology for deriving a satellite-driven surface energy balance for estimating ET from the earth’s surface and have the potential to become widely adopted by water resources communities, provided regional calibration and validation should be there in localized region [77].

In southern Idaho, southern California, and New Mexico, METRIC has been applied with high resolution Landsat images and ET was mapped [78] and it also showed progression of ET according to stage of growth. Results were compared with Lysimeter and ET by traditional methods on daily and monthly basis for a variety of crop types and land uses. Error in estimated growing season ET was 4% for irrigated meadow in the Bear River basin of Idaho and 1% for an irrigated sugar beet crop near Kimberly. Standard deviation of error for time periods represented by each satellite image averaged about 13 to 20% in both applications. They concluded that METRIC is also promising, efficient, accurate and inexpensive procedure to estimate evapotranspiration.

In Regge and Dinkel, Netherlands, Actual Evapotranspiration [79] was estimated through SEBS model using summer time Landsat images, meteorological
and groundwater data. The spatial and temporal variation of AET was done for the study areas with different landuse classes. Ground truth data was not available for validation so reference ET and kc approach was used for validation of SEBS model.

In the Perfume River Basin, Hue, Vietnam, study was carried to map evapotranspiration by a spatial hydrological model [80] called STREAM, was used which require minimum levels of input data. Data required for STREAM model was only precipitation and temperature. SEBAL (Surface Energy Balance Algorithm for Land) was applied to calibrate the model. In this study SEBAL helped to calculate evaporative representation of the catchment without proceeding into detail field data collection on the actual spatial pattern of the land cover type of the catchment area.

Soil Moisture Atmospheric Coupling Experiment (SMACEX) over the Walnut Creek watershed in Iowa multiple satellite sensors [Landsat-ETM (60 m), ASTER (90 m), and MODIS (1020 m)] were used to estimate evapotranspiration [81] by remote sensing. Results were compared with eddy covariance flux measurements. Close agreement was observed between the retrievals from the higher-resolution satellite platforms (Landsat-ETM and ASTER). The MODIS-based estimates were unable to identify land surface heterogeneity at the field scale, but by illustrating the utility of this sensor for regional-scale it can be done.

In Southern Great Plains, ET was estimated from MODIS and AVHRR sensors for clear sky days through remote sensing technique [82] and for validation, results were compared with the estimated ET results to ground flux stations. RMSE (Root mean square error was found to be 53, 51 and 56.24 W m\(^{-2}\) and coefficient of correlation was found to be of 0.84, 0.79 and 0.77 from MODIS, NOAA16 and NOAA14 sensors respectively.

At the end if we compile the review of all Remote Sensing Models, it can be said that each algorithm has own advantages and disadvantages, but in spite of their advantages and disadvantages these models are important tools for estimating evapotranspiration on a regional scale. In S-SEBI model, no additional ground based measurement is needed except surface temperature and albedo.

SEBAL model used in this study has numerous benefits as compared to other models. In this model within the each analysed satellite image, automatic internal
calibration is done, which decreases the sways in estimation of surface roughness and aerodynamic stability correction. This calibration also reduces the requirement for atmospheric correction of Ts or reflectance (albedo) measurements using radiative transfer models[83]. The other biggest advantage is that it calculates actual ET instead of potential ET and moreover no information of crop type is required even no need of satellite based crop classification. SEBAL model is strongly dependent on theoretical and physical relationships but automated calibration of empirical coefficients make this model more accurate and operational on practical basis [47]. Owing to all these facts SEBAL model is extensively used for various agricultural crops as well as in variety of ecosystems and climates, provided it should be validated in that particular agro climatic zones. Though in mountainous areas, SEBAL results are not very accurate. These problems have been resolved in METRIC model.

It is also found that Land Surface Temperature (LST) is most crucial factor affecting the accuracy of the ET estimates. In addition to this emissivity, surface albedo, soil moisture, fractional vegetation cover, Leaf Area Index and Normalised Difference Vegetation Index also affect the accuracy of Evapotranspiration [60]. It is also very important to give special attention while retrieving these surface variables. Even than Remote Sensing ET models can provide accurate spatial distributions of instantaneous ET, provided the fact that there should be clear sky conditions and that is too on instantaneous scale, at the same time for simulating long term development trend of the soil water content, turbulent heat fluxes, and other related processes [84], in land surface process models are used. Thus the integration of both types of models may substantially improve the estimation and monitoring of the land surface fluxes.

There is real growth in the field of computer processing techniques along with rapid improvement of multi-spectral, multi-spatial, and multi-temporal satellite technology and optimization of remote sensing models. The linkage between the remote sensing and hydrological models will be vital for most future applications in the field of water resources management.

The outcome of these studies has indicated that SEBAL/METRIC models have high potential for successful ET estimation and can be done in semi-arid areas of USA by comparing the derived ET with lysimeter observations [84]. This
statement cannot be given for Indian climatic conditions because extensive validation of remote sensing model is not done in these climatic conditions. Among various problems in ET estimation, validation is one of the most troublesome problems, particularly because of both the scaling and the advection effects. To overcome this problem, various validation methods can be developed which may include comparison of ET derived from remote sensing and ground-based measurements over same location, verification of ET derived from satellite data at different spatial resolution or obtained by integrating various data sources in land surface process models is essential.

2.4 Experimental Methods to measure evapotranspiration

Evapotranspiration can be measured by various experimental methods but most important and widely used methods are Eddy Covariance Method and Lysimeters.

2.4.1 Eddy Covariance Method

It is also one of the experimental method to measure evapotranspiration. In this method sensible and latent heat fluxes are measured directly. Eddies are turbulent airflow caused by wind, the roughness of the Earth’s surface, and convective heat flow at the boundary between the Earth’s surface and the atmosphere. Water vapor, heat, and other scalars like carbon dioxide transferred by eddies can be measured directly using the eddy-covariance method. It also avoids soil surface heterogeneity issues by placing the sensors above the crop canopy and the evapotranspiration can be measured from various type of vegetation. It is a statistical method used in meteorology and other applications (micrometeorology, oceanography, hydrology, agricultural sciences, industrial and regulatory applications, etc.) to determine exchange rates of trace gases over natural ecosystems and agricultural fields, and to quantify gas emissions rates from other land and water areas. The experimental studies to measure ET by eddy covariance method are presented here.

In southern Arizona USA, study was conducted to determine the accuracy of eddy covariance ET measurements by comparing them with ET derived from small watershed water balances[85]. Thirteen years of data from shrubland, grassland and
savanna sites was compared. Both the savanna and the shrub land had very similar closure measures whereas the grassland differed. This may be due to greater topographical relief at the grassland, means additional degree of uncertainty in this analysis due to the spatial-scale mismatch between the two estimates of ET.

A study was conducted to estimate ET for a 7-year period over a lowland Dipterocarp forest in Pasoh, Peninsular Malaysia, using the eddy covariance method[86]. Annual rainfall fluctuated between 1,451 and 2,235 mm during this period. Despite inter-annual variation in rainfall, annual evapotranspiration was stable, except for a slight decrease in the driest year (2009). Evapotranspiration was roughly related to the amount of available energy, but was regulated by stomatal closure to prevent excessive water loss at high vapour pressure deficit.

In USA, a study compared ET estimates based on field eddy covariance measurements over two growing seasons (May–October) with computer simulation modeling results in eight dominant ecosystems in a managed landscape in Northern Wisconsin[87]. Comparisons of field data and modeling results were useful in quantifying ET flux at multiple temporal scales, especially as the accuracy of field sampling techniques.

2.4.2 Lysimeters

Lysimeters are tanks contained soil and crops are grown with field conditions to directly measure the water loss by evaporation and transpiration [88-89]. By Lysimeter direct measurement of crop evapotranspiration (ETc) is done. It is also used to study climatic effect on of crop evapotranspiration (ETc). Its construction is like that it prohibits the vertical flow and distribution of water. To install the lysimeters in ideal conditions, it needs various requirements so that lysimeter data should be representative of field conditions. Lysimeters can be grouped into three categories:

1. Non-weighing, constant water-table type

   In this ET is computed by adding measured quantities of irrigation water, the effective rainfall received during the season and contribution of moisture from
soil. In this constant water level is maintained by applying water. Effective rainfall is measured by raingauge.

2. Non-weighing, percolating-type

In this constant water level is not maintained as in constant water table type. ET is computed by adding measured quantities of irrigation water, the effective rainfall received during the season and the contribution of moisture from the soil

3. Weighing types Lysimeter

In this ET is measured by taking weight of the tank and making adjustment for any rain. It provides most accurate data. Weighable Lysimeters provide a good recording of evapotranspiration, owing to this fact they are used more frequently.

In the present study lysimeter technique has been adopted as a validation technique, because this is one of the most accurate and tested method, here few case studies are mentioned where evapotranspiration is measured by Lysimeter.

Experiments on Lysimeter were started since more than two decades like at the College of Forestry in northern Sweden [90] and to investigate about the assembly and performance of Lysimeters and the studies found that the dynamic Lysimeter was mechanically stable, functioned satisfactorily and was easy to set up in the field.

By Terrestrial Environmental Observatories in Europe (TERENO) in Germany [91] changes in the hydrological cycle due to climate change were monitored at 12 sites with a total of 126 lysimeters and they developed a strategy for development and testing of guidelines for the determination of P and ET from lysimeter measurements and also defined procedure to evaluate the accuracy of determining net P and ET fluxes from large precision lysimeters.

In Bahia, Brazil [92], study was done for designing, installation and calibration of Lysimeter for crop evapotranspiration. They used the load cell based weighing platform and electronic data recorder and found it more appropriate and also they used tunnel that allowed access to the space underneath, the inner tank is highly
recommended not only for collecting drainage water but also for inspection of weighing platform integrity and maintenance.

In Southeast region of the United States [93] electronic weighing Lysimeters were designed and constructed for monitoring reference (grass) crop and to develop crop coefficient curve, but due to variation in environmental conditions, including rainfall from one growing season to the next, affecting crop-growth and crop-water use patterns, it is difficult to estimate precisely. Further crop coefficient functions also varied greatly among seasons, development of a single “average” crop coefficient curve was difficult.

In Bangladesh [94] a study was performed on four Lysimeters with one cubic meter effective volume, the Lysimeter was tested by experimenting with lentil crop (Lens culinaris). The performance was found satisfactory. Similarly in Italy [95] a study was performed on mini Lysimeters because they are cheaper than traditional Lysimeters, so these are affordable. But for a correct measurement, it is important to maintain the measurement area meadow in good conditions in order to limit micrometeorological effects.

Various studies mentioned above in which evapotranspiration was estimated by Remote sensing models, validation of these studies was carried out by experimental methods and out of experimental methods Lysimeter and eddy covariance methods were considered most accurate methods. Present study is also validated by Lysimeter experiments conducted at WTC, IARI, and New Delhi.

2.5 Chapter Conclusion

Following major conclusions are drawn from the above chapter are mentioned below:

• Evapotranspiration is crucial and important component of Hydrologic Cycle and various studies reported empirical methods to estimate evapotranspiration in different countries.

• Amongst empirical methods, FAO-56 Penman-Monteith method was adapted as a standard method in various studies and is widely used for the validation of estimated ET data measured using other empirical methods.
• Different energy balance models to estimate evapotranspiration based on remote sensing technique were also developed and evapotranspiration was estimated in various countries using these models.

• Surface Energy Balance Algorithm for Land (SEBAL) was considered as one of the most versatile remote sensing based method for estimating ET of very large and heterogeneous area accurately.

• Experimental methods also exist to estimate evapotranspiration and Lysimeter method to calculate evapotranspiration was considered as accurate experimental method. But these methods have certain limitation and cannot be used for composite terrain.