Chapter 2

Review of Literature

2.1 Introduction

The irrigated agriculture uses large chunk of water, thus a big responsibility lies with irrigation managers to efficiently use the water. The large quantity of water is lost as evaporation and transpiration from the fields. Evaporation and transpiration usually happen at the same time and is hard to separate the two processes. To match the irrigation supply with demand, estimation of the evapotranspiration is required to be done with appropriate methods, which can give reasonably good accuracy. FAO presented two publications to describe various model for estimating crop water requirements (Doorenbos and Pruitt, 1977; Allen et al., 1998). In view, of the recent development in data acquisitions, and techniques to model soil water crop interaction, selection of appropriate model needs the understanding of capabilities and limitations of each available model. In this chapter review is done, of most of the widely used methods available to estimate reference evapotranspiration based on climate data. Points to be considered for selection of appropriate method are also suggested.

2.2 Evapotranspiration

Evapotranspiration is the combined process through which water is lost by evaporation from the soil surface and from the crop by transpiration. The crops require a fixed quantity of water to meet the water losses through evapotranspiration, for bumper crop production under standard conditions.

Allen et al. (1998) in FAO-56 defined crop evapotranspiration (ET_c), under standard conditions refer to crops that are disease-free, well fertilized, and are grown in large fields, under optimum soil water with excellent management and environmental conditions, so as to attain full production, under the given climatic conditions. ET_c measurement is not easy and requires sophisticated, expensive equipment, and trained research personnel with varied range of systems.

Lanthaler (2004) reported measuring evapotranspiration using lysimeter.

Phene et al. (1990); Cammalleri et al. (2010); Allen et al. (2011) and Evett et al. (2012) illustrated that evapotranspiration data, could be obtained from varied range of measurement systems, which included lysimeters, eddy covariance, Bowen ratio, scintillometry, sap flow, satellite-based remote sensing, direct modeling, and soil water balance, such as gravimetric, neutron probes, electromagnetic types of soil sensors, and time domain reflectometry etc.

Direct measurement techniques are not feasible for estimating evapotranspiration in large irrigated area. Mostly they are used for research purposes by trained personnel. Evapotranspiration is generally estimated, by using different methods, which requires measurements of climatological parameters.

2.2.1 Empirical and Temperature Based Methods

Pan Evaporation Method

Evaporation pan provided measurement of integrated effect of temperature, radiation, wind, and humidity on evaporation from a particular open water surface.

Cuenca (1989), Allen et al. (1998) utilized evaporation pan data to convert evaporation from free-water surface with pan coefficient to estimate potential evapotranspiration. They demonstrated that incorrect accounting for pan environment and local climate could cause errors in estimation of crop water use up to plus or minus 40 percent.

Temperature Based Methods

Hedke (1924), Blaney and Morin (1942, Lowry and Johnson (1942), Thornthwaite (1948), Blaney – Criddle (1950, 1962), Phelan (1962), and Doorenbos and Pruitt, (1977) developed method for areas, where available climatic data covered air temperature data only. Procedure for adjusting monthly *k* values, as a function of air temperature was developed which is known as SCS Blaney Criddle method. Researchers included other meteorological variables to improve estimate of potential evapotranspiration, popularly known as FAO Blaney-Criddle method. Doorenbos and Pruitt, (1977) concluded that radiation method would be more reliable than Blaney Criddle in equatorial regions, on small islands, or at high altitudes even if measured sunshine or cloudiness data were available.

The empirical and temperature based methods have been used for estimating evapotranspiration for longer periods i.e. monthly or weekly.

2.2.2 Radiation Methods

Evapotranspiration occurs only when energy is available, and hence estimation of solar radiation can give better estimation of ET, by using Energy Balance equation, which includes R_n (radiation from sun and sky), G (heat to ground), H (heat to air).

Makkink (1957), Turc (1961), Jensen-Haise (1963), and Hargreaves-Samani (1985) proposed a formula for estimating ET from air temperature and sunshine or cloudiness or solar radiation. The Makkink equation was the base of the subsequent FAO 24 Radiation method.

In spite of sufficient energy available, ET could be less due to aerodynamic resistance in form of Wind speed and Humidity as for the atmosphere's ability to remove water vapour, an 'aerodynamic' strength also plays a crucial role.

2.2.3 Combination Methods

Penman (1948, 1963) utilized Bowen ratio principle and derived a combination equation by coalescing two terms, one (radiation) term, which was for the energy required to uphold evaporation from open water surface, and second (wind and humidity) term for the atmosphere's ability to remove water vapour, an 'aerodynamic' strength.

Various researchers proposed modification in the Penman equation. Wherein, Monteith (1965, 1981) extended Penman's basic concept to plants and cropped areas. Priestly and Taylor (1972) simplified Penman's equation for humid environments. Doorenbos and Pruitt (1975, 1977) modified Penman method with a revised wind function term, and an adjustment for mean climatic data, for estimating reference crop ET. Wright (1982) modified the original Penman equation and adapted 1982 Kimberly-Penman equation. Kizer et al. (1990) developed hourly evapotranspiration prediction model, by calibrating the Penman equation for an alfalfa reference crop.

Allen et al. (1998) used the equation on hourly basis with the r_s term, having a constant value of 70 s m^{-1} throughout the day and night. They recommended FAO-56 Penman Monteith method as the sole standard method, for determining reference evapotranspiration in all climates, especially when there was availability of data.

Allen (2000) developed REF-ET program, which provided standardized reference evapotranspiration calculations in different time steps, for more than 15 methods commonly used, such as Pan Evaporation, Temperature methods, Radiation methods, and Combination methods.

Allen (2002) compared the seasonal reference evapotranspiration estimated by ASCE standardized Penman-Monteith, with 1982 Kimberly Penman and found the differences to be low.

Walter et al. (2005) developed a standardized reference evapotranspiration equation, which could be applied to two types of reference surfaces alfalfa and clipped grass, for daily and hourly calculation time step. The ASCE Standardized Reference Evapotranspiration Equation based on FAO-56 Penman-Monteith equation was developed by ASCE-EWRI task committee with aforesaid purpose. The equation is also recognized as *ASCE-EWRI standardized Penman-Monteith equation*.

Allen et al. (2006) reviewed the functioning of FAO-PM method, using surface resistance parameter r_s = 70 sm^{-1} in hourly time step, while using a constant r_s = 50 sm^{-1} during day, and r_s = 200sm^{-1} during night for hourly period.

The latest developed standardized ASCE-EWRI equation would be great help to the researchers, for precisely estimating reference evapotranspiration irrespective of the reference crop chosen. The widely used equations discussed above are depicted in Table 2.1. Values for C_n and C_d in FAO-PM and ASCE-EWRI standardized PM equations are given in Table 2.2

2.2.4 Comparison Studies of Methodologies

Comparison studies have been carried out worldwide, regarding the functioning of methods to estimate reference ET. Each method has its own strengths and weaknesses under the particular set of conditions. Here studies have been discussed to give an idea about their functioning.

Hatfield and Allen (1996) compared ET estimates under deficient water supplies with Priestly-Taylor and Penman-Monteith equations. Penman-Monteith gave more consistent results, while Priestly-Taylor overestimated ET_c.

Dodds et al., (2005) reviewed various methodologies to estimate ET_{ref}. (i) Evaporation Class-A pan tended to be 7-8 percent higher than the locally calibrated ET_o values for evaporation rates. (ii) Two methods of Penman combination Equation with certain variation in it were compared with lysimeter. a) Kohler-Parmele variation was with a purpose, of calculating the long wave radiation from the soil-plant system using the air temperature, instead of evaporating surface temperature. b) Morton gave an iterative variation, of the Penman equation to calculate a suitable evaporating surface temperature. Both methods performed well.

Berengena and Gavilan (2005) compared measured ET_o using lysimeter, with estimated ET_{ref} in a highly advective semi arid environment. They found that locally adjusted Penman and ASCE-PM gave the best results, followed by FAO-PM. Hargreaves equation under predicted for high ET values, and the Priestly-Taylor equation was found to be too sensitive to advection, and the values improved only after the application of correction of the Jury and Tanner.

Er-Raki et al., (2010) compared three empirical methods Makkink, Priestley-Taylor and Hargreaves-Samani, for computing reference evapotranspiration (ET_o) to those with FAO Penman-Monteith in semi arid climate. Hargreaves equation tended to under estimate ET_o, upto twenty percent for daily periods. Makkink, and Priestly and Taylor methods, clearly under estimated the values of ET_o, during dry periods in comparison to FAO-PM model, since values of $\alpha = 1.26$ and $C_m = 0.61$, that were used are suitable for humid conditions.

Artificial Neural Networks (ANNs) could be a useful tool to estimate reference evapotranspiration, as a function of climatic elements (Kumar et al., 2002; Jothiprakash et al., 2002). Chauhan and Shrivastava, (2012) reported that ANNs performance were better, when compared with lysimeter measured values, than those obtained from Penman-Monteith method for estimation of ET_{ref}. Ojha and Bhakar (2012) carried out the comparison between daily ET_{ref} estimated by Penman Monteith (PM) method, and that of estimated by ANNs, and found the ANNs results encouraging.

Table 2.1: Equation and Measured data required for ET_o prediction for various methods

Name of Prediction Method	Equation	Data used
Empirical and Temperature Methods		
Hedke (1924)	Heat available = Temp x days	T
Blaney and Morin (1942)	$PET = rf(0.45\ T_a+8)(520 - R^{1.31})/\ 100$	T,SS,RH
Lowry and Johnson (1942)	$CU = 0.00185\ H_E + 10.4$	T
Thornthwaite (1948)	$e = 1.6(10t.I^{-1})^{\alpha}$	T,SS
Blaney and Criddle (1945,1962)	$f = T.p/100$	T,SS
SCS-Blaney Criddle Phelan(1962)	$ET = \sum_{i=1}^{n} k_{ti}k_i f_i = K\sum_{i=1}^{n} k_{ti} f_i\ ;\ k_{ti} = 0.0173T_i - 0.314$	T,SS
US Weather Bureau Class A pan	$ET_o = K_p E_{pan}$	RH,E,W
FAO-Blaney Criddle Doorenbos & Pruitt (1977)	$ET_o = a + b[p(0.46T_a + 8.13)]$	T,SS,RH,W
Temperature and Radiation Methods		
FAO radiation (Makkink, 1957)	$ET_o = c(W\ R_s)$	T,SS,RH,W ,R_s
Turc(1961)	$ET_o = a_T\ 0.013\frac{T_{mean}}{T_{mean}+15}\frac{23.8856R_s+50}{\lambda}$	T,RH,R_s,
Jensen and Haise (1963)	$ET = (0.014T_f - 0.37)R_s$	T, R_s
Hargreaves and Samani (1985)	$ET = 0.0023TD_c^{0.5}(T_c + 17.8)R_a$	T, R_s/(SS^1,R_a)
Combination Methods		
Penman (1948,1963)	$\lambda E = \frac{[\Delta(R_n - G)] + (\gamma\lambda E_a)}{(\Delta+\lambda)}$	T,SS,RH,W ,R_s
Penman-Monteith method (Monteith 1965)	$ET = \frac{\Delta(R_n - G) + \rho c_p(VPD)/r_a}{\Delta + \gamma(1+\frac{r_s}{r_a})}$	T, RH, R_n
Priestly and Taylor(1972)	$ET_o = 1.26\frac{\Delta}{\Delta+\gamma}\frac{(R_n - G)}{\lambda}$	T, RH, R_n
Modified Penman method, Doorenbos and Pruitt (1975,1977)	$ET_o = c[W.R_n + (I - W).f(u).(e_a - e_d)]$	T, W, R_n
1982 Kimberly Penman Method, Wright (1982)	$\lambda ET_r = \frac{\Delta}{\Delta+\gamma}(R_n - G) + \frac{\gamma}{\Delta+\gamma}6.43W_f(e_s - e_a)$	T, RH, W, R_n
Penman equation for hourly ET for alfalfa, Kizer et al., (1990)	$LE = \frac{\Delta}{\Delta+\gamma}(R_n + G) + \frac{\gamma}{\Delta+\gamma}W_f(e_s - e);$ $W_f = a + bU_2$	T, RH, W, R_n
FAO-56 Penman-Monteith Method, Allen et al., (1998)	$ET_o = \frac{o.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1+0.34u_2)}$	T, RH, W, R_n
ASCE-EWRI standardized - PM method, Walter et al., (2005)	$ET_{sz} = \frac{0.408\Delta(R_n - G) + \gamma\frac{C_n}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)}$	T RH, W, R_n

T = Temperature, SS = Sun shine hours, RH = Relative Humidity, W = Wind, E = Evaporation, R_s= Solar Radiation, R_n = Net Radiation.. PET= Potential evapotranspiration (mm day^{-1}), T_a= Mean monthly temperature in ^oC, R= Mean monthly Relative humidity, rf = ratio of monthly to annual radiation. CU= Annual consumptive use (inches), H_E= Effective heat, in degree days above 32^o F. e = unadjusted potential ET (cm/month)(month of 30 days each and 12 hrs daytime t= mean air temperature(^{o} C), I = annual or seasonal heat index, α= an empirical exponent. f= monthly consumptive use factor, T = mean monthly temperature (^{o} F), p = monthly per cent of total daytime hrs of the year. ET= Seasonal crop water requirements (inches), k_i= monthly Blaney Criddle coefficient, f_i = monthly consumptive use factor, T_i= mean temperature for month i, (^{o} F). ET_o= Reference evapotranspiration (mm day^{-1}), K_p= Pan coefficient, E_{pan} = Pan evaporation (mm day^{-1}). a, b = climatic calibration coefficients , p = mean daily percentage of total annual daytime hours, T_a= mean daily temperature in ^{o} C over the month considered. c = adjustment factor depending on mean humidity and daytime wind conditions, W = function of the temperature & altitude, R_s= solar radiation (mm day^{-1}). a_T = coefficient depending mean relative humidity, R_s= solar radiation (MJ m^{-2} day^{-1}), λ = latent heat of vaporization (MJ kg^{-1}). $T_f$and T_c = mean air temperature (^{o} F and ^{o} C), R_a = extraterrestrial radiation (mm d^{-1}) , TD_c = maximum and minimum daily air temperature difference. λE = evaporative latent heat flux (MJ m^{-2} day^{-1}), Δ = slope of saturated vapour pressure curve (kPa $^oC^{-1}$), R_n= net radiation flux (MJ m^{-2} day^{-1}), G = sensible heat flux into the soil (MJ m^{-2} d^{-1}), γ = psychrometric constant (kPa $^oC^{-1}$), E_a = vapour transport of flux (mm d^{-1}). ρ = density of air (kg m^{-3}), c_p = specific heat of moisture (J kg^{-1} $^oC^{-1}$), VPD = vapour pressure deficit, r_s and r_a = canopy surface resistance and aerodynamic resistance (sm^{-1}). W = temperature related weighting factor, f(u) = wind related function, $e_a - e_d$ = difference between saturation vapour pressure at mean air temperature and the mean actual vapour pressure of air (both in mbar), c = adjustment factor to compensate for the effect of day & night weather conditions. ET_r = reference evapotranspiration (MJ $m^{-2}d^{-1}$), W_f = wind function. LE = mean hourly latent heat flux (Wm^{-2}), U_2 = wind speed at 2m (km h^{-1}), a and b = coefficients. e_s = saturation vapour pressure (k Pa), e_a = mean actual vapour pressure (k Pa), C_n and = C_d numerator constants and denominator constants respectively that change with reference type and calculation time step $(\mathrm{K\,mm\,s^3Mg^{-1}d^{-1}}$ or $\mathrm{K\,mm\,s^3Mg^{-1}h^{-1}})$ and $(\mathrm{s\,m^{-1}})$.

Table 2.2: Values for C_n and C_d in Equation for the FAO-PM and ASCE-EWRI standardized PM equations (Allen et al., 1998; ASCE-EWRI, 2005)

Method	Calculation time step	C_n	C_d
FAO-PM (ET_o) & ASCE-PM (ET_o)	24-h	900	0.34[c]
	Hourly	37	0.24/0.96[a]
ASCE-PM (ET_r)[b]	24-h	1600	0.38
	Hourly	66	0.25/1.7[a]

[a] The first value for daytime periods (when R_n>0) and the second value is for night time.
[b] ET_r is reference ET from 0.5m tall alfalfa.
[c] The C_d= 0.34 is now recommended to be changed to 0.24 for daytime and 0.96 for night time for hourly or shorter time steps.

Irrigation is supplied to compensate the moisture deficit in soil occurred due to evapotranspiration. Hence, precise estimation of ET is required. The factors affecting potential ET are radiation, temperature, relative humidity, and wind speed. The measurement techniques provide the point value of moisture content, and it cannot be used to estimate the crop water requirement of large irrigated area with varied climate. The empirical and temperature based methods performed suitably under specific climatic and agronomic conditions, for which they were originally developed, and could not be used under different conditions, other than that for which they were developed. Transferring these to other regions led to either, under/over estimation causing substantial errors. The radiation methods which considered the radiant energy, provides better estimates in humid climate, but were less precise in advective conditions in arid and semi arid climates, and hence it needed adjustment or correction. The combination methods take into account the radiant energy term as well, as aerodynamic term the ability to remove water vapour hence, it improved upon the ET estimation. FAO-PM was considered the sole standard method, in case all the climate data are available. ASCE-PM method was standardized for different reference crops, and also for different calculation time step. The ASCE- PM standardized reference ET equation is widely accepted for precise estimation of ET. This method can provide important tool, for developing decision support system for irrigation scheduling. The relationship of ET and climate parameters is complex and hence, many researchers have resorted to data modeling such as ANN technique.

2.2.5 Estimation of Crop Evapotranspiration Using Crop Coefficient and Other Approaches

Precise estimation of evapotranspiration, with an appropriate method is required to congregate demand and irrigation supply. Recent development in climate data acquisitions has facilitated researches in estimating evapotranspiration, by selecting an appropriate model, for soil water crop interaction. Various methods to estimate crop evapotranspiration using crop coefficient, and other approaches are reviewed in this study. Researchers propagate either one step direct estimation of ET, or indirect step i.e. crop coefficient approach. The crop coefficient approach is widely used because of its simplicity. They are classified as single crop coefficient and dual crop coefficient. Amongst, the two crop coefficient approach, single and dual; the dual crop coefficient gives precise estimates of crop water requirement, especially during light & frequent wetting events. New concept of near surface soil storage developed by Rushton et al., (2006), and relationship developed by Sanchez et al., (2012) between NDVI, LAI, FVC, and K_{cb} to improvise the FAO-56 estimations of ET & soil moisture are discussed.

Review of various methods to estimate crop evapotranspiration using crop coefficient, and other approaches and their applicability, and effectiveness are discussed here.

Approaches for Estimating ET

Evapotranspiration for irrigated crops is estimated with two different alternative methodologies: i) One step, or direct approach, and ii) Two step approach, or indirect approach.

One step or direct approach of estimating evapotranspiration is recommended by many researchers as it gives directly the crop ET.

Monteith (1985) suggested adopting more direct approach to estimate crop water requirements, known as one-step method, or direct Penman-Monteith.

Allen et al., (1998) recommended that, by adjusting albedo, aerodynamic, and canopy surface resistance to the growing characteristics, of the particular crop the ET rate could be estimated directly. ET is estimated individually of each crop, by combining the meteorological data with physiological (stomatal) & boundary layer resistances of each crop.

Shuttleworth (1976, 2006) used one step approach and derived equations, for converting widespread K_c into surface resistance r_s, and on substitution of these surface resistance r_s into P-M equation; it provides an opportunity to make one-step estimate of crop evapotranspiration ET_c, from the values of K_c using 2 meter climate data.

The limitation, of measuring directly the water flux path resistances from a crop, has lead to the normal use of second method i.e. Two step or indirect approach of estimating evapotranspiration, also known as crop coefficient approach.

Two step approach or indirect approach is also known, as crop coefficient approach.

Doorenbos and Pruitt (1977) and Allen et al., (1998) explained the Two step approach, in which evapotranspiration is estimated for single reference crop, and then rate of evapotranspiration of the single reference crop (ET_o) is related to evapotranspiration rate, of the various crops (ET_c) with help of crop coefficients (K_c). They may refer to two types of reference crops, clipped, cool season grass, or tall alfalfa, which is denoted by (ET_o), or (ET_r) respectively.

Van Wijk and de Vries (1954) initiated a method to estimate ET using coefficients.

Jensen (1968) proposed estimating evapotranspiration by two- step process, by using the rate of evapotranspiration from a well-watered alfalfa with 30-50 cm of growth as reference crop, and multiplying it with crop coefficient. Jensen (1969) carried out estimates for alfalfa reference evapotranspiration (ET_r) using computerized irrigation scheduling program developed at Kimberly. Jensen et al., (1990) stated that the two-step approach produced estimates of ET_c within the accurateness of most farm-irrigation systems to supply water.

The two step approach of FAO-56, considers climate related factors by ET_{ref} term, and crop related factors by crop coefficient K_c. The characteristics of the crop such as vegetation ground cover, canopy surface resistance, and aerodynamic resistance of the crops, which are grown in the field, are different than the reference crop. These effects of characteristics distinct, from reference crop are incorporated in the crop coefficient. The deviation in transpiration and evaporation, of reference crop from field crop is either integrated in a single crop coefficient K_c, or it can be separated into two coefficients, basal crop coefficient K_{cb} and soil evaporation coefficient K_e. i.e. ($K_c = K_{cb} + K_e$). Based on this approach, the crop coefficient is adopted as single coefficient to estimate combined value, or dual coefficients which consider the two processes separately.

Single Crop Coefficient

The single crop coefficient is generally used for non frequent wettings, and to calculate ET in daily, or ten- days, or monthly time step.

Allen et al., (1998) noted that generalized crop coefficient values used, for the single crop coefficient (K_c) (equation 2.1) approach were suitable, for sub-humid climates having average values of about 45 percent for daily minimum relative humidity, and calm to moderate average wind speed of $2ms^{-1}$, while for other climatic conditions adjustments were recommended.

$$ET_c = K_c \times ET_o \qquad (2.1)$$

Hunsaker et al., (2003a) reported that generalized K_c could give errors in estimating ET_c, since local development of K_c requires measuring ET_c, during the entire growth season. It would be unwise on practitioners part to use published values for their crop, because of empirical nature of K_c, as it limits the transferring them into places, where the management factors and local climate deviates, from the conditions for which the tabulated value were developed.

Ko et al., (2009) developed regionally based growth-stage specific (K_c), and also determined crop water use for cotton & wheat.

Piccinni et al., (2009) carried out similar studies for maize and sorghum at Texas. They concluded that the usage of K_c developed for other regions would effect in either over- or under irrigation, and consequently increase production costs, or reduced profits, while the regionally developed based K_c could help greatly in irrigation management with LEPA (low energy precision application) systems, or subsurface drip irrigation.

Dual Crop Coefficient

The dual crop coefficient is prevalent more nowadays, due to computing facilities available in hourly and daily time step, for frequent wetting events, especially required for drip and automated centrally pivoted sprinkler system. In case, of small precipitation, or frequent wetting events the evaporation from the top thin layer would be comparatively fast & large. This would have a great impact on evapotranspiration calculations, while estimating soil evaporation especially during initial stages, when the vegetation ground cover is less. To account for these situations, researchers were conducted on soil, and hydrologic water balance using Dual crop coefficient to improve ET_c estimates as per equation 2.2. (Allen et al., 1998)

$$ET_c = (K_{cb} + K_e) \times ET_o \tag{2.2}$$

Various researchers attempted dual crop coefficient approach.

Ritchie (1972) made efforts to develop models by measuring evaporation and transpiration separately.

Shuttleworth and Wallace (1985) developed a functional soil evaporation model for partial cover using the dual approach and the two-source model (S-W model).

Wright (1982) measured evapotranspiration over various crops with weighing lysimeter, and introduced the idea of the basal crop coefficient, representing the conditions when evaporation from soil was minimal, and most of the evapotranspiration was transpiration.

Heermann (1985) expressed that in future, models would need precise estimates of evapotranspiration, and some would need separating evaporation and transpiration.

Lafleur and Rouse (1990) and Farahani and Bausch (1995) noticed that *ET* for crops with partial cover was underestimated during the early season by P-M.

Allen et al., (1998) made efforts to develop models by measuring evaporation, and transpiration separately, under pristine conditions (where no limitations are there on crop growth or evapotranspiration) and non pristine conditions. They estimated the values of basal crop coefficient of various crops and predicted the effects of specific wettings on its value.

Hunsaker (1999); Hunsaker et al., (2003a) showed that the dual procedure could give high-quality estimates, of daily evapotranspiration for full-irrigated cotton, sorghum and alfalfa respectively. Allen, (2000) used dual crop coefficient approach of FAO-56, which included prediction of soil evaporation separately, and compared it with remote sensing estimates of ET; and concluded that approach was useful for operational applications where estimates of ET_c were needed on daily basis.

Allen et al., (2005) reported that dual crop coefficient was more relevant for evaporation calculations, and precisely appropriate for scheduling with frequent wetting, while carrying out comparison and performance of single and dual crop coefficient.

Consoli et al., (2006) estimated ET_c of different-sized navel-orange tree orchards, using energy balance with different irrigation methods, and found crop coefficient values to be higher, than the values stated in FAO24 and FAO56, for high-frequency drip irrigation, micro-sprinkler irrigation and border irrigation.

Chuanyan and Zhongren (2007) estimated water requirements of maize, using the daily determined K_{cb} values, and predicted the seasonal changes in the ET_c .

Liu and Luo (2010) on comparing ET_c, and K_{cb} got through FAO-56 with the lysimeter found, that the K_{cb} was effective in quantifying winter wheat seasonal evapotranspiration, but was imprecise in calculating the peak values.

Descheemaeker et al., (2011) derived crop coefficients for semiarid natural vegetation, using logarithmic relation between vegetative soil cover and K_c.

Rosa et al., (2012) developed SIMDualKc software application, incorporating standardized procedures of FAO-56, for the dual Kc method. The model separated evaporation, into soil wetted by both irrigation and precipitation, and that wetted by precipitation only.

Fandino et al., (2012) computed crop evapotranspiration of vineyards in presence of active ground cover, with the dual K_c approach, and tested SIMDualKc model for the same. The K_{cb} values are estimated by developing K_c curve as suggested in FAO-56. It can also be computed based on NDVI obtained from remote sensing, or field measurements.

Hunsaker et al., (2003b) developed and evaluated K_{cb} estimation model, derived through the observations of the normalized difference vegetation index (NDVI) for full season cotton. The K_{cb} functions based on NDVI were incorporated in the dual crop coefficient procedures of FAO-56. The main benefit of using real-time multispectral-based K_{cb} in place of conventional

K_{cb} curves was to eliminate the necessity to hypothesize the time-scale, for crop developmental stages, and future weather conditions, for a specified cropping season.

Tasumi et al., (2005) evaluated the distribution of K_c over spatial and temporal, for large number of individual fields by crop type, using ET maps created, by satellite base energy balance model. They found large variation in K_c curves, when compared with NDVI because of the effects of random wetting events on K_c, especially during initial and development growth stages.

Er-Raki et al., (2007) tested three methodologies to find basal crop coefficient K_{cb}, and field cover f_c for winter wheat. The foremost approach used K_{cb} tables of FAO-56, and f_c was calculated from those values, the second approach used locally calibrated K_{cb} values, and field measured f_c values, and the third approach used calibrated Normalized Difference Vegetation Index (NDVI) based on ground remote-sensing vegetation indices to estimate K_{cb} and f_c. They concluded that the K_{cb} values of FAO-56 needed local calibration, especially for mid season as the value 0.9 was considerably lesser, than the value of 1.1 as recommended in FAO-56.

Sanchez et al., (2012) presented and analyzed the relationships between the vegetation indices NDVI, leaf area index LAI, fraction of vegetation cover FVC, and basal crop coefficient K_{cb}, with a plan to improvise the FAO-56 estimations of evapotranspiration & soil moisture. They evaluated the K_{cb} influence on the estimation of soil moisture.

The dual crop coefficient approach as it separates transpiration, and evaporation helps in estimating impacts of irrigation, or rainfall frequency, or irrigation system type on total crop water requirements. When the contribution of evaporation from the soil is significant, the use of dual crop coefficient approach provide better estimates of ET.

There are many simple and popular models used by researchers, which use single crop coefficient approach such as CROPWAT. Some advanced models like WEAP, SIMDualKc etc., use dual crop coefficient to precisely estimate crop water requirement. Estimating crop coefficient using NDVI approach is prevalent, because of availability of remote sensing data and GIS tools. NDVI approach needs to focus on improving upon estimates, during initial and developing growth period.

2.3 Soil Moisture Balance

The crop transpires at potential rate, under standard conditions. The water stress results in reduction in evapotranspiration rate. Soil moisture balance models give a helping hand to researchers to monitor the soil water status, the inflow, outflow through the water lost by ET, and deep percolation. In view, of the recent development in data acquisitions, and techniques to model soil water crop interaction; selection of appropriate model needs the understanding of capabilities, and limitations of each available model.

Rao, (1987) showed that soil moisture content is a critical state variable, that determines the response of a soil- crop system to any water input. Continuing monitoring of soil moisture content is of great significance in irrigation management.

Allen et al., (1998) emphasized the need to estimate the water stress on daily basis, using the soil water balance model for the root zone, wherein the root zone is represented as container in which the water content fluctuates. The inflow into the container was through rainfall, irrigation, and capillary rise of groundwater, while outflow comprised of crop transpiration, soil evaporation, and deep percolation losses. The daily water balance equation is denoted by equation (2.3) as follows:

$$D_{r,i} = D_{r,i-1} - (P - RO)_i - I_i - CR_i + ET_{c,i} + DP_i \quad (2.3)$$

Where , $D_{r,i}$ is root zone depletion at the end of day i (mm), $D_{r,i-1}$ is water content in the root zone at the end of previous day i-1, (mm), P_i is precipitation on day i (mm), RO_i is runoff from the soil surface on day i (mm), I_i is irrigation on day i (mm), CR_i capillary rise from ground water table on day i (mm), ET_c crop evapotranspiration on day i (mm), and DP_i is deep percolation losses on day i (mm).

Sarr et al., (2004) developed a water balance model which took into account soil water status, and leaf development of plant. The model expressed evapotranspiration as a function of simulated soil water status, and the observed leaf area index (LAI). The model considered soil as a reservoir divided into two compartments, where the relative sizes varied in time with root growth.

Rushton et al., (2006) developed a single store soil moisture balance model, to represent moisture conditions within the soil zone. They estimated actual evapotranspiration both during growing season, and during stages, when evaporation from bare soil was the major component. Limitations of the conventional single store model, which is unable to represent transpiration, or evaporation on days following significant rainfall, even though soil moisture deficits are higher than the readily available (evaporable) water was overcome, by introducing the new concept of near surface soil storage.

Prats and Pico (2010) demonstrated that computer models could be of great help to estimate the soil water balance, and for developing and evaluating various irrigation strategies. They concluded that amongst the various hydraulic properties of soil, Total Available Water (TAW) was the most significant one, for evaluating the performance of irrigation scheduling.

Allen (2011) introduced a new concept, and enhanced the formulation in the simple ‘slab’ soil water evaporation model of the FAO-56. Used the ‘readily evaporable water’ (REW) term of the original model to accommodate, such events of light wetting that have a tendency to wet the soil surface ‘skin’ and evaporate comparatively fast. This newly introduced concept reverted for the time being into stage 1, for evaporation, and increased evaporation estimates, when small precipitation events occurred. This improved accuracy in estimation, especially when light and frequent precipitation events occurred. Wherein, wetting events weren’t frequent the evaporation, and water balance was correctly worked out over time, as per original FAO-56 model in spite of water being completely mixed in the evaporation slab. The improved FAO-56 evaporation model compared well against HYDRUS 1D model, and recorded observations of weighing lysimeter.

Dogrul et al., (2011) developed models to compute water demands by routing the root zone moisture in an integrated hydrology. Soil moisture balance in root zone was calculated considering the land-surface flows along with the urban and agricultural water demands at basin scale in the context, of integrated surface, and sub- surface hydrology.

Kumar (2013) presented a new methodology with step-by-step procedure to estimate the ground water recharge in unsaturated zone, by integrating the theory of SCS method in a modified soil moisture balance approach to find the storage index.

In soil moisture balance “Skin” layer effect suggested by Allen et al., (2011) has enhanced the ET estimates substantially, as it takes into account frequent wetting events. The near surface soil storage concept developed by Rushton et al., (2006) can precisely estimate the transpiration, or evaporation on days, following significant rainfall, which can help in irrigation scheduling on real time basis. As, water is becoming scarcer, the effect of climate change, resulting in moisture deficit in tropical regions is compelling irrigation managers to resort to water saving technologies, wherein dual crop coefficient approach could play an important role. Input of irrigation water in soil moisture balance is derived, from adopted irrigation scheduling techniques, which can have a vital impact on crop yield and water savings.

2.4 Irrigation Scheduling

It is the process of determining the proper time, and the proper amount of water required to be applied for irrigation. There are various approaches, which are employed in irrigation scheduling namely- transpiration ratio approach, soil moisture deficit approach, irrigation depth-interval-yield approach, water-balance accounting approach, critical stage approach, visual plant symptoms approach, and simulating evapotranspiration by models. The irrigation scheduling can be accomplished for full or partial crop water requirement. Deficit irrigation or partial crop water requirement is practiced, when there is water scarcity, or when irrigation system capacity is limited. The purpose of irrigation scheduling is to efficiently use the water, and assist the farmer in maximizing the crop yield. The views and work on irrigation scheduling by various researchers are as follows:

Doorenbos and Kassam (1979) presented that maximum potential yield is attained, if standard conditions are maintained throughout season of the crop, but under significantly reduced soil moisture conditions the yield is reduced. They further emphasized on having the precise knowledge of crop response to water, as drought tolerance varied as per growth stage and crop species.

Rao et al., (1988) developed a mathematical model for irrigation scheduling in weekly intervals, with the objective of maximizing crop yield, under a limited seasonal supply of water. They determined water - deficit index to quantify crop water stress in specified periods of growing season, based on actual evapotranspiration. Further, developed dated water-production functions (to determine crop sensitivity factors to water deficits in specified periods of growth), by evaluating the effects of alternative combinations of crop water deficits in the various periods on crop yield. The constraints of the optimization models were derived from a weekly soil-water balance model.

Palmer et al., (1989) studied the various sources of non uniformity of flows in irrigation scheduling, where the water delivery were scheduled flexibly, as per farmers requested timing, rate, and duration. Irrigation flows, which varied unpredictably affected the performance of the irrigation system, and defeated the sole purpose of flexible scheduling. They concluded, to provide large flow rates of shorter duration intervals, in order to attain better uniform deliveries.

Howell et al., (1990) and Howell et al., (1995) demonstrated that highest WUE and IWUE usually, occurs at an evapotranspiration generally less, than maximum evapotranspiration ET_c. Declines in IWUE with increasing irrigation were usually associated with soil water storage, drainage, excessive soil water evaporation, and runoff, or if water deficit occurred at a critical growth stage.

Mannocchi and Mecarelli (1994) stated it was feasible to model relationship between crop yield, and water applied by using crop yield response factor equation.

Tolk et al., (1997) determined the sorghum growth, water use, and yield in contrasting soils. Crop in silt loam soil produced greater grain yield under reduced irrigation, and lower grain yield under high soil water conditions compared to the crop, in the clay loam. Crop in sandy loam produced lowest yield in all irrigation conditions, possibly due to low water holding capacity and high soil bulk densities, which could have restricted rooting growth. They concluded that soil type affected water use, growth, and yield of grain sorghum, wherein crop in the silt loam extracted water uniformly, throughout the horizon, while crop yield was reduced in high soil water conditions created due to poor drainage.

Zhang and Oweis (1999) conducted ten years of supplemental irrigation experiments, in order to evaluate water-yield relations for wheat, and to propose optimal irrigation scheduling for various rainfall conditions in the Mediterranean region. Deficit irrigation varied from 20 per cent to 80 per cent of the full irrigation water applied, in different levels of supplemental irrigation treatments. The water stress sensitive to growth stages for wheat were from stem elongation to booting, anthesis, and grain filling. Crop yield enhanced with rise in evapotranspiration above the threshold of 200mm. They concluded that irrigation scenarios for maximizing crop yield under limited water resource conditions, for the wheat in the region should not be recommended, as a curvilinear relationship of yield with the total applied water was found. Sparse water should be applied at crop-growth stages that were more sensitive to water stress. Irrigation during booting to grain filling would be proper for improving water use efficiency when probability of rainfall was low in such an environment.

Kirda et al., (1999a) and Kirda (2002) determined that as, crop yield response factor K_y increases, water use efficiency (E_c) decreases, which implies that benefit from deficit irrigation is unlikely in case of K_y greater than unity. Significant savings in irrigation water through deficit irrigation can be obtained, when the crop yield response factor (K_y) is less than 1 during the entire season, or growth stage. Before implementing deficit irrigation, it is necessary to know crop yields response to water stress, either during defined growth stages or throughout the whole season.

Kassam and Smith (2001) provided an overview of developed FAO methodologies (FAO 24, FAO 33, FAO 46, and FAO 56) for computing crop water requirements, crop water use efficiency and crop water productivity under deficit and adequate irrigation for traditional farm practices. Discussed water supply strategies for optimal crop production under deficit irrigation, and advised farmers to optimize timing and application rate of irrigation under limited water supply. Suggested that policies be framed in accordance to plans and strategies to achieve food requirements under limited water supply and drought conditions for both irrigated and rainfed agriculture. Further, they recommended evaluating strategies to optimize yields, by reducing risks of crop failure, by keeping in mind crop choice, sowing time, cultural practices with options of water conservation, and supplemental irrigation.

Alderfasi and Nielsen (2001) developed a baseline equation to compute crop water stress index CWSI, for checking of water status and scheduling irrigation in wheat. Remotely sensed infrared tool was used, for evaluating crop water status. The CWSI was computed with help of the baseline equation of D2=0.41-1.5 x AVPD, and substituting it in the formula of $CWSI= \{[(T_c-T_a)-D_2]/ [D_1-D_2]\} \times 10$, where T_c is average plant canopy temperature (^oC), T_a the air temperature (^oC). The value of D_2 was (T_c- T_a) predicted from the baseline equation (lower limit of T_c- T_a); while D_1 was the upper limit of T_c-T_a, which was equal to 2^oC in winter wheat.

Moutonnet (2002) determined that crop response factor estimates relative yield reductions, based on the measured reduction in crop transpiration. The crop yield response factor K_y varies depending on species, variety, irrigation method and management, and growth stage, when deficit evapotranspiration is imposed.

Smith et al., (2002) reported that the water stress results in less evapotranspiration, by closure of the stomata, thereby reducing absorption of carbon, and decrease in biomass production. Any restriction in the supply of water is likely to induce a decrease in evapotranspiration, thereby resulting in decrease in WUE.

Molden (2003) reported that the crop water productivity or water use efficiency was key term in the evaluation of deficit irrigation strategies.

Tolk and Howell (2003) evaluated the effect of soil type, soil water use characteristics, and seasonal climatic differences on the WUE and IWUE, of grain sorghum grown in the semi-arid climate. Simulated deficit irrigations keeping limited water availability in mind and gave irrigation treatments accordingly. Observed that generally, IWUE declined with increasing irrigation application within each year, but was variable in some irrigation treatments, due to water stress at critical growth stages. Further, no differences among soil types occurred in IWUE in either year. Crops grown in the Amarillo soil had significantly higher WUE compared with crops in other soils, primarily due to reduced ET, rather than increased yield.

Jalota et al., (2006) studied the influence of soil texture, precipitation, and deficit irrigation system, through analyzed simulation of their interaction on crop water productivity in cotton wheat cropping system. Results showed that by decreasing the economic optimal irrigation water quantity below 400 mm, for both crops the yield and ET were reduced. Reduction in crop water productivity (CWP) was noticed with decrease in post sowing irrigation water to 75 mm from 300 mm. Reduction in CWP, for silt loam, sandy loam, and loamy sand soils were 15 percent, 4 percent and 1 percent for cotton; and 8 percent, 36 percent and 55 percent for wheat respectively. Larger decrease in CWP was observed for wheat in comparison to cotton, and for coarse textured soils than fine-textured soils respectively. Crop growth stages found to be more sensitive to water stress were from flowering to boll formation in cotton and grain development in wheat. Concluded, that lesser supply of water than economic optima (400 mm for both crops), through reduced number of irrigations is of no use to enhance real crop water productivity RCWP (Marketable yield / ET). RCWP was decreased due to comparatively extra decrease in yield, than ET because of lesser number of irrigations; while apparent crop water productivity ACWP (marketable yield/irrigation water) increased.

Raes et al., (2006) and Sieber & Purkey (2011) demonstrated that the water stress in the crops is not constant throughout the growth period, but occurs in different magnitude at different growth stages. Thus they emphasized the necessity to compute relative yield fraction at smaller time step i.e. daily, and multiplicative product of the yield fraction of all days be used, as relative yield fraction for the season.

Timsina et al., (2008) carried out studies to explore the potential, for enhancing CWP and IWP of wheat, by maneuvering the date of sowing and irrigation management in the Indian state of Punjab. After the calibration of the model, results suggested that irrigation scheduling be done according to the soil water status or atmospheric demand, and not as per the growth stages. Studies showed that yield, CWP and IWP would maximize, when irrigation was applied according to soil water deficit and crop sown on the optimum date (i.e. Nov. 10).

Tolk and Howell (2008) determined the amount of field water supply (sum of irrigation, precipitation, and available soil water at planting), after which reduction in water productivity and irrigation water productivity occurred due to non evapotranspiration losses (i.e.

percolation, excessive soil water evaporation, and soil water storage in the profile), under various irrigation treatments (0 percent, 25 percent, 50 percent and 100 percent replacement of evapotranspiration). Irrigation application of 100 percent, demonstrated large amounts of non evapotranspiration irrigation application losses in the finer textured soils, which resulted in reduced water productivity and irrigation water productivity. The yield response on enhancing field water supply was linear for coarser-textured soil, because of gradual increase in the non evapotranspiration losses, such as drainage with the increase in irrigation application amount.

Gontia and Tiwari (2008) correlated canopy-air temperature difference, and vapour pressure deficit for winter wheat crop, under no water stress conditions (i.e. baseline equation), which helped in quantifying crop water stress index (CWSI) for scheduling of irrigation. The lower (non stressed) and upper (fully stressed) baselines were empirically established with the canopy, and ambient air temperature data, using infrared thermometry and vapour pressure deficit (VPD), under full irrigation and maximum water stress condition for crop. Monitoring the water status for wheat crop, and planning of irrigation scheduling was possible with the determined CWSI values.

Geerts and Raes (2009) reviewed selected research, from around the globe and summarized advantage, and limitations of deficit irrigation. Results confirmed that deficit irrigation was a great success in enhancing water productivity, for a variety of crops without having severe reductions in yield, provided a secured minimum quantity of seasonal moisture was ensured. As, CWP function were non-linear, crop specific and they often differed by phenological stage, genotype and location, they discussed about crop water production function which allowed first assessment of agronomic usefulness of applying deficit irrigation in a specific situation. It was suggested that the field research be combined with thoroughly calibrated and validated crop water productivity models, to improvise deficit irrigation strategies derived from field experiments.

Pereira et al., (2009) used full irrigation and a range of deficit irrigation strategies to handle water scarcity problem for cotton crop. Results showed that when the available irrigation water was very inadequate, the strategies which lead to relative high losses i.e. (larger than 15 percent) should not be selected. Further, it was observed that when deficit irrigation strategies were adopted, there was more proper use of ground water and available soil water. Comparison between the simulated schedules showed that on imposing heavy irrigation deficits, it lead to comparatively high yield losses, while the water productivity and the economic water productivity increased only slightly. Thus, when small farms were considered, implementing such strategies raised questions, especially from an economic point of view. Finally, it was concluded on analyzing several deficit irrigation strategies, through the respective potential water saving, relative yield losses, water productivity, and economic water productivity, that adopting relative mild deficits was a better proposal. Contrarily, the adoption of high water deficit that produce high water savings would lead to yield losses that may not be economically acceptable.

Ko et al., (2009) used Environmental Policy Integrated Climate (EPIC) model as a decision support tool, for irrigation management of maize and cotton. Model simulated the various crop yields, for diverse irrigation regimes. Relationships between yield and crop evapotranspiration, for both cotton and maize were not absolutely linear, but showed an exponential curve upto a lower quantity of crop evapotranspiration, and then followed a linear pattern onwards. The results showed that water application above ~700 mm water input, or ~650 mm of crop evapotranspiration for maize; and 700-900 mm of water input, or 650-750 mm of crop evapotranspiration, for cotton would not only be surplus, but lead to inefficient crop water use.

Davis and Dukes (2010) determined the efficacy of irrigation scheduling of three brands of evapotranspiration-based irrigation controllers, and compared it to a theoretically determined soil water balance model. The Weatermatic controller, Toro controller and ETwater controller were used for scheduling irrigation. First two mentioned controllers utilized a feature to pause rain; wherein the ETwater controller pauses the irrigation for certain days as determined. The Weathermatic controller, Toro controller and ETwater controller irrigated less by 3 percent, 27 percent and 46 percent compared to theoretical requirements.

Cakir and Cebi (2010) demonstrated the effect of irrigation scheduling, and water stress on the maturity and chemical composition of tobacco leaf. Concluded, that severe water stress caused delay in ripening of leaves. Good moisture conditions, either for the period of the sensitive growth stages, or during the total growing season, severely reduced the nicotine and nitrogen content of tobacco leaves. Both of them in large amount are considered hazardous for humans. At the same time, with increased seasonal water amounts there was enhancement in chloride content which results in decreasing the burning quality of tobacco.

Ahaneku (2011) carried out studies on the infiltration characteristics, and crop productivity of two mostly found agricultural soils in north central Nigeria. They concluded that crop productivity could be influenced by the infiltration characteristics, the soils having high infiltration rate could store water, which would be helpful to crops sown early in case the rainfall is not constant. The results indicated that sandy loam soil had more favorable physical properties than sandy clay loam, as far as run-off reduction and infiltration ability were concerned.

Oweis et al., (2011) studied crop evapotranspiration and water use, under full and deficit irrigated cotton in the Mediterranean environment of northern Syria. They developed water productivity functions by relating cotton yield to crop evapotranspiration, as well as initial available water in soil profile at sowing time. Functions were helpful in optimizing irrigation and predicting the water rationing, and drought impact on water budgeting for the region.

Dwivedi et al., (2012) studied the effect of pre-puddling tillage and puddling intensity on irrigation water productivity in rice. They concluded that pre-puddling tillage and puddling intensity played a vital role in enhancing both irrigation water saving and rice yield.

O'Shaughnessy et al., (2012) examined the efficacy of the crop water stress index and time threshold, to control irrigation without human intervention of long and short season grain sorghum, and checked the crop response to deficit irrigation treatments (i.e. 80 percent, 55 percent, 30 percent, and 0 percent of full refill of soil water depletion to 1.5 m depth). Automated irrigation scheduling results were similar & supporting the use of CWSI-TT, as an efficient method for scheduling of grain sorghum, when compared with manual irrigation applied using weekly neutron probe readings. This method provided a better alternative to farmers, who could install moving sprinkler systems having sensor networks outfitted, for automatic control and nonstop feedback of plant water condition to manage irrigation scheduling, instead of using neutron probe for measurement of soil water.

Discussion: Irrigation scheduling if required to be carried out for shorter intervals would not be possible, if model is developed on weekly basis as in case of Rao et al., (1988). If curvilinear relationship is achieved between the crop yield and total irrigation applied, then irrigation water should not be applied then the upper threshold limits, under limited water availability scenarios as observed by Zhang and Oweis (1999). Policies for irrigated agriculture are needed to be framed under limited and drought conditions for both irrigated and rainfed conditions for choice of crop, sowing time, change in cultural practices keeping in view water conservation and supplemental irrigation as suggested by Kassam and Smith (2001). Review of the researchers demonstrated that Yield and ET are reduced, if water is decreased below the economic optimal irrigation. IWUE declines with increasing irrigation, thus a balance is required to be maintained to see that neither, less irrigation or over irrigation is applied. Adopting relative mild deficit irrigation is a better option rather than high water deficit, as with higher water deficits, yield loss is greater, which may not be acceptable to cultivators even, if it gives high water savings. Planning of irrigation scheduling is possible by determining crop water stress index values and monitoring the water status. To manage irrigation scheduling without human intervention is possible nowadays, using sensor networks outfitted for automatic control and nonstop feedback of plant water condition as stated O'Shaughnessy et al., (2012), which could be useful in deciding alternative sets of irrigation scheduling. While, adopting irrigation strategies it is also necessary to control rising of groundwater due to deep percolation by conjunctive use of surface water and groundwater.

2.5 Irrigation Strategies to Promote Conjunctive Use

To use optimally the overall water of the area, including surface and groundwater over a period of time in a harmonious manner is recognized, as the most suitable strategy for irrigation development. Conjunctive use mitigates the problems of water logging, salinity and facilitates the use of saline ground water by dilution with surface water.

Ejaz and Peralta (1995) developed an optimization model to determine the use of reclaimed water in conjunction with river and groundwater, while ensuring that water quality constraints were met.

Qureshi et al., (2004) evaluated the long term effects of management strategies employed in semi-arid areas of Punjab, Pakistan, for the conjunctive use of surface water and groundwater, with varying quality of irrigation water on root zone salinity. They found, that in areas of fresh groundwater (EC = 1.0 dSm^{-1}), mixing groundwater and canal water with a 1:1 ratio, provided adequate leaching of salts below the root zone, and minimized the danger of yield reduction. In areas of marginal groundwater (EC = 1.5 dSm^{-1}), the direct use of groundwater reduced transpiration rate by three percent, compared to mixing groundwater and canal water in a 1:4 ratio. Further, in years of below average rainfall, the transpiration rate could reduce more upto ten percent, due to soil salinization in the root zone. In areas of saline groundwater (EC > 2.7 dSm^{-1}), the direct use of groundwater or conjunctive use in any ratios would be completely disastrous, with salinity levels reaching upto 20 dSm^{-1} in just 2-3 years, thereby making crop production impossible.

Brown et al., (2006) designed pricing system for groundwater, keeping in focus the inter-annual changeability of monsoon rainfall & the dynamic cost of groundwater use, for state of Tamil Nadu, India. Pricing system calculated approximately the marginal social cost of groundwater use, on the basis of existing state of aquifer storage and the incoming monsoon forecast. Prices were put up before the onset of the monsoon, so farm managers could plan crop rotations according to expected seasonal rainfall, as depicted in the pricing signal. The objective was to suggest a method that transformed probabilistic categorical forecasts into a decision algorithm for water managers. Water tariff was decided using expected total marginal cost equation, and opted for the price that maximized the social benefit. The linear optimization model generally used for generating demand curves were used, for simulating the farmer's choice of crop planning, under each water price scenarios. Net income and water used for each crop plan, under three monsoon scenarios above normal, normal, below normal were calculated accordingly, and the subsidy determined on that basis were then transferred to the farmer. The higher prices were charged when the forecast was for a deficient monsoon, encouraging conservative cropping pattern and water conservation.

Shah et al., (2006) emphasized on paradigm shift, required in conjunctive management of ground water and surface water, by concentrating on augmenting groundwater recharge through recharge structures. They concluded that enhancing of groundwater recharge was needed to increase percolation from surface runoff and rainfall, to sustain groundwater use in tube well irrigated areas.

Bharati et al., (2008) developed a coupled economic-hydrologic simulation-optimization model, with an objective of exploring conjunctive irrigation water use strategies in the Volta Basin. The model together consisted of physical hydrology model WaSiM-ETH and an economic optimization model.

Adhikari et al., (2009) evaluated the priority water rights of the farmer managed irrigation system (FMIS), in the head reaches in view, of a water supply scenario at the extension area of the Babai Irrigation Project, Nepal. They worked out dry season irrigation strategy to be implemented by storing the surplus discharge of the monsoon and autumn in local ponds; then using them in dry periods in the extension area based on the remaining flow. They suggested the conjunctive use of groundwater, canal waters and harvested water stored in local reservoirs for sustainable irrigation water management in the region.

Foster et al., (2010) provided an overview of prevailing practices of conjunctive use of groundwater and surface water, for both urban water supply and irrigation. They emphasized on the approaches to overcome the technical, social, institutional and economic hurdles coming their way, for promoting more rational and efficient conjunctive use.

Karimov et al., (2012) applied procedure for water accounting, by recognizing both the possibilities of savings and employing strategies which would be beneficial. They suggested three strategies. First Strategy- (a) Increasing farming practices to maximize agricultural yield where water table were 1.0 to 1.5 m. (b) Increasing transpiration and reducing evaporation, by enhancing overall crop water productivity by switching over to multi-cropping and intercropping, instead of single cropping practices in the region . Second Strategy- (a) To decrease evaporation from high water tables; the canal and/or drainage system be rehabilitated to lower water table, where the water table was in range of 1.5 to 2.5 m. (b) Suggested employing water saving, by alternate furrow irrigation. Third Strategy- (a) Promote conjunctive use of groundwater and canal water, and also ground water banking (where water table was below 3m) to reduce both flows to sinks and pollution. (b) To reduce ground water pollution by substituting shallow wells instead of deep wells.

Kazmi et al., (2012) studied the impact of conjunctive use, of canal and tube well water in Lagar irrigated area, Pakistan. They found varied reactions of farmers, because of disparity in access to canal water and tube well water, in downstream and upstream areas. They found that because of lower costs for electrically operated tube well, farmers of downstream areas were lured to irrigate with saline groundwater. Upstream areas were less dependent on groundwater, than downstream areas due to availability of canal waters. In Kharif season, the head users used mainly canal water, the tail users used groundwater and the centre used both canal, and ground water to irrigate rice crop. Salt accumulation was observed in centre and tail fields due to irrigation with slightly saline groundwater. They concluded, by emphasizing the need to frame policies, so as to restrict extraction from aquifers, and focus on demand and supply management strategies.

Al Khamisi et al., (2012) explored the prospects of using reclaimed water (RW) from Sewage Treatment Plant (STP), for irrigated agriculture without Aquifer Storage and Recovery in conjunction with ground water in Oman. They recommended, transferring reclaimed water to areas where ground water of good quality was available. Rather, than transferring the reclaimed water to areas predominant with saline ground water which were unsuitable for irrigation, thereby preventing disposal of reclaimed water to the sea, and minimizing stress of fresh ground water zones. The areas of cropping of Wheat, Cowpea, and Maize could be enhanced by 323 percent, 250 percent and 318 percent respectively, against utilization of reclaimed water only. Of total irrigation requirement, 57.6 percent was met with reclaimed water and 42.4 percent was met with ground water.

The above studies proposed conjunctive use of surface and groundwater. Conjunctive use of groundwater, canal water, and harvested water stored in local reservoirs is required, for sustainable irrigation management. Enhancing of groundwater recharge needs to be done to increase percolation from surface runoff and rainfall, to sustain groundwater use in tube well irrigated areas. Increasing of farming practices, multi cropping, and use of groundwater be done, where water table is high. However; certain precautionary measures are required to be taken during promoting conjunctive use of surface water and groundwater. (1) In areas of saline groundwater (EC > 2.7 dSm^{-1}), the direct use of groundwater, or mixing of surface and groundwater in any ratios, and using for agriculture should be forbidden. (2) Groundwater pricing be not static but dynamic, and be decided keeping in focus inter-annual changeability of monsoon rainfall. Subsidy in pricing is provided during normal, or above normal monsoon and higher prices be charged, when forecast would be of deficient monsoon to encourage conservative cropping pattern and water conservation. (3)The electricity charges be fixed not so low, that farmers are lured to opt for groundwater even if saline, rather than canal water, as was observed in Pakistan. (4) Reclaimed sewage water is required to be transferred to places having good groundwater quality, rather than places having saline groundwater, which were unsuitable for irrigation. Models could be of great use in assessing and evaluating irrigation scheduling/ management strategies.

2.6 Application of WEAP Model in Irrigation Management

The Water Evaluation and Planning (WEAP) model has been developed by Stockholm Environment Institute U.S.A. WEAP model is a tool, for water resources planning works, as it operates on basic principle of water balance accounting. WEAP provides a system for water demand and supply information. It can be used as a forecasting tool and policy analysis tool. WEAP has incorporated MABIA method which simulates transpiration, evaporation, irrigation requirements and scheduling, crop growth and yields. It includes various modules, for estimating reference soil water capacity. The MABIA method uses the dual crop coefficient method, where crop coefficient values are divided into basal crop coefficient, $K_{cb,}$ and a separate component, K_e, representing evaporation from soil surface. The basal crop coefficient represents actual evapotranspiration conditions when the soil surface is dry, but sufficient root zone moisture is available to support full transpiration. This way WEAP is an improvement over CROPWAT, which uses single crop coefficient approach, and does not separate evaporation and transpiration Sieber and Purkey (2011). Reviews of few researchers have been discussed here.

Lévite et al., (2003) used Water Evaluation and Planning System WEAP as a research tool, to simulate and analyze water allocation scenarios in river basins, taking into account variations in abstractions, demands, and ecosystem requirements. They found WEAP model as potentially useful tool, for a rapid assessment of water allocation decisions in a river basin, in particular to locate geographically, where the problems were likely to occur. User-friendly interface added capability of facilitating dialogue among the various stakeholders with an interest in water allocation and management in the basin.

Groves et al., (2008) developed a method of applying uncertain information, about projections of potential global climate change, from atmosphere-ocean general circulation models (AOGCMs) to local- and regional- scale water management models. Analysis using the Water Evaluation and Planning System (WEAP) model showed that climate change had a greater impact on the region, by increasing the outdoor water demand by ten per cent, while decreasing the local water supply and sustainable groundwater yields by forty per cent and fifteen per cent respectively by the year end of 2040.

Yates et al., (2009) developed a comprehensive water resource modeling framework developed for the Sacramento Basin, California using Water Evaluation and Planning Version 21 WEAP21. The model bridged the gap between watershed hydrology and water management. The model was able to adequately capture the overall mass balance of the Sacramento Basin. WEAP facilitated an analysis of alternative future climate scenarios. Approach was useful for water planning activities, by weighing the advantages, and disadvantages of various management decisions available such as, change in supply, or stick to moderate use, increasing surface storage, reusing wastewater, conjunctively managing surface supplies and groundwater basins, increasing water use efficiency, and desalinating sea water, especially in the face of climatic change.

Esteve et al., (2015) presented a hydro-economic model to assess potential effects of climate change on irrigated agriculture and options for adaptation. They combined a farm-based economic optimization model with the hydrologic model WEAP. Results show that climate change may impact severely irrigation systems, by reducing water availability and crop yields, and increasing irrigation water requirements. Applied framework proved to be a useful tool, for supporting water and climate change policymaking.

Chokshi et al., (2012), Bhatti and Patel (2015a) determined actual evapotranspiration, for crop using Penman Monteith Method and dual crop coefficient approach using MABIA, which is incorporated in the WEAP model. They found FAO- 56 Penman Monteith model very useful to precisely estimate daily potential evapotranspiration, using daily climatological data. Bhatti and Patel (2015b) evaluated five different irrigation strategies, for cotton crop using dual crop coefficient approach. Dual crop coefficient approach computed separately soil evaporation and transpiration under normal and water stress condition. Saving of water was achieved, by application of model using WEAP in determining irrigation requirements in real time condition.

Ahmed et al., (2015) estimated potential and actual crop evapotranspiration, of the major crops cotton and wheat, sown in the Hakra 4R canal command area in Pakistan using WEAP model. They found that the difference between potential and actual crop evapotranspiration was high during the months of August and September 2012, for cotton crop and for Wheat crop, during March and April Months.

WEAP application allows the simulation and analysis of various water allocation scenarios. Water demand management is possible with WEAP. Simulations are possible for diverse climatic situations from dry years to normal years. The irrigation scheduling can be done with various strategies, such as triggering irrigation at fixed interval, fixed depletion, percentage of depletion, percentage of readily available water and percentage of total available water. The amount of irrigation could be applied according to fixed depth, percentage of depletion, percentage of readily available water and percentage of total available water. The ease of use of the model and its user-friendly interfaces make it particularly useful for evaluating various irrigation strategies.

2.7 Studies Related to Sardar Sarovar Project

The Narmada Planning Group (NPG) multidisciplinary team of professional experts was formed by Government of Gujarat, which recognized the need of database, for project planning considering the complexity and size of project. Group of experts from all fields commissioned 25 technical studies covering aspects, such as reservoir simulation, dynamic programming, groundwater simulation, groundwater investigation, supplies from the en route rivers crossed by Narmada Main Canal, canal losses, studies on cross drainage works, operation plan for distribution system of sample areas, and special problems of Narmada Main Canal. Twenty socio- economic studies covering variety of subjects were commissioned by NPG such as cropping and land use patterns, water requirements and regional allocation of water, water use and management policy, distribution system layout, study on ecology and environment, to explore for the development of agro based industries etc. Out of many of the studies; which were planned, or under taken in SSP, few of them have been reviewed over here.

Sehgal et al., (1982) carried out mathematical modelling on behalf of ORG Vadodara to model the groundwater basin in Baroda-Bharuch area of the Narmada-Mahi Doab. They studied specified scenarios projecting changes in water levels, due to increase in pumping and increase in recharge, due to surface irrigation. Obtained GWRDC data showed average June-October fluctuations in water levels, of the order of 1.5 m to 2 m per year, for the period 1970-1979. A recharge of 210 mm was considered, for the monsoon period, for average rainfall of 1100 mm. In absence, of any additional ground water development and an input of 500 mm per year per unit of CCA would cause additional recharge of 130 mm per year to the groundwater system. This finally would lead to 37 percent of area with water table at ground-level or within 2m of it, at the end of the Kharif at 10^{th} year. Further, noted that if at the end of 10^{th} year of surface irrigation, additional pumping is introduced at four times the present rate, then the water logged area at the end of five years would be 30 percent and 19 percent of the area of Kharif and Rabi respectively. If pumping was continued then after 15 years the water logged areas would decrease significantly. They emphasized the need of studies to be undertaken, for evapotranspiration and irrigation return and examine the following: (1) the amount of irrigation seepage, (2) the amount of water delivered to crops, (3) types of crops and tree cover, and (4) quantity of water consumed by evapotranspiration.

Pathak (1989); Alagh et al., (1995) and Pathak (2011) explained that number of technical and socio-economic surveys have been undertaken, particularly on dam site and the reservoir, sub-surface geology for major structures on rivers, planning of distribution systems and fixing water requirement, soil surveys, evaluation of groundwater regime and its behaviour under varying conditions. Detailed simulation model were set at Indian Institute of Management, Ahmedabad and Operations Research Group (ORG), Vadodara to carry out water accounting on basis of 10-day flow and try to match supply and demand pattern, as generated through agricultural plans. Extensive modeling exercise was under taken by ORG to simulate behaviour of groundwater, under varying irrigation conditions. Studies were carried out for weighing the benefits, for using the available water for irrigation, or hydropower electric generation. A systematic computer based transient modeling study was under taken, for main canal with objective of distributing the water without causing any problems. To ensure the lands do not get water logged due to canal irrigation, a comprehensive drainage study was under taken for Narmada Mahi Doab. Environmental impact of SSP was carried out by The Maharaja Sayajirao University of Baroda. Narmada command being highly heterogeneous in respect of agronomic features, therefore during planning the area was divided into 13 homogeneous regions. A set of agronomical feasible crop combinations and crop sequence was prepared and Net irrigation requirements for the crops were worked out on the basis of modified Penman's method. Fifty percent dependable fortnightly rainfall was used in the analysis. Overall irrigation water use efficiency was considered as 60 per cent. Region wise fortnightly water demands for chosen crop sets were worked out to arrive at peak water demands. Pre-feasibility level study has been carried out for assessing the drainage requirements of Narmada-Mahi doab. Detailed studies were carried out of ground water reserve balances for whole command and specifically for Narmada-Mahi doab with calibrated conjunctive use model of canal and groundwater. Conjunctive use of canal water and groundwater has been planned keeping in mind to prevent water logging and salinity of agriculture fields with the objective of maximizing benefits. After studying the physical characteristics of land, aquifer characteristics, ground water table reserves and rainfall of all the regions, water availability of groundwater in command was estimated considering the recharge due to irrigation and rainfall. It was decided to use ground water reservoir as a source along with canal water for balancing the demand and supply for entire command for future years to come ahead. Finite difference iteration digital model was used for ground water modelling studies for region between Narmada-Mahi with an objective to study the rise of ground water over a time period by varying the recharge due to rainfall and irrigation. The summary of the results indicated as follows: (a) A draw down greater than 1.5 m in 14 per cent of modelled area would be achieved over a period of ten years, in case of ground water irrigation is done in an scenario prior to implementation of project, provided the ground water abstraction was enhanced by 50 percent to the existing rate over a period of five years. (b) If existing rate of abstraction was not enhanced, and surface irrigation water is applied at 500 mm/year then at the end of ten years there would be rise in water table upto ten meters or more in 36 percent of the area. (c) In order to avoid water logging in the region the pumping may have to be increased four times to the existing one, if supplementary pumping is delayed ten years from the start of project irrigation. (d) In case supply of surface irrigation water is maintained between 500-700 mm along with strategy of conjunctive, by enhancing pumping upto 184 percent than water logging problem is not so severe, and can be handled with surface drainage system. (e) In case of extreme situation of applying surface water upto 1000 mm the scenario shows water logging area reaching upto 55 per cent just at the end of consecutive seventh Kharif period. Anticipated draft on full ground water development of SSP for region I is 290 MCM and 599 MCM respectively. Fortnightly water demands for agriculture and non agriculture for region I was worked out and summed up for yearly, which was about 1186 million cubic meter, while the annual canal withdrawals and groundwater withdrawals, for region 1 was 907 and 279 million cubic meter respectively, similarly this was also done for all regions. Anti-water logging and salinity measures were inbuilt in planning design and operation of the system. Some of the prominent features of water management plan were: (1) Limited water delta of 53 cm against the normal 75 cm in existing irrigation projects; (2) volumetric and rotational water supply by warabandhi; (3) conjunctive use of surface and groundwater; (4) provision of surface and sub-surface drainage; (5) lining of entire canal network upto 8 hectare block to minimize seepage losses; (6) remote controlled automatic canal operation; (7) water balance and salt balance studies and monitoring; (8) encouragement of micro-irrigation; and (9) participatory irrigation management.

Shah (1995) undertook groundwater modeling studies and soil salinization on behalf of H R Wallingford Ltd. U. K. for regions 2, 11 and 12 in SSP command area. Results indicated that four parameters, that influenced salt build up in root zone in order were soil type, salinity of irrigation water, irrigation efficiency and initial soil salinity. It was observed that salt build up was much higher in clay soils than on sandy soils. In region 2, the salt buildup was higher than salt tolerance limit of paddy only when ECmix was higher than1.5 mmhos/cm. For all other crops salt built up was lower than salt tolerance limits. Leaching could be considered for paddy if soil was fine clay and applied irrigation was less than 1.2 NIR. Results of the studies would be of great help in conjunctive use planning for use of groundwater in the command area.

Desai (2011) explained that credible estimates were made in SSP command project region wise, which shows that 2.71 MAF of useable groundwater is available to be used conjunctively. Unusable groundwater to be wasted by pumping that required to be disposed of from partially bad and bad areas is 0.66 MAF. It also mentioned that assessment was done after detailed groundwater surveys and mathematical modeling, for estimating the recharge in the Phase I command, through specialized international agency Mott MacDonald, which found assessment of groundwater and conjunctive use quite realistic.

Jagadeesan and Dineshkumar (2015) found significant difference in groundwater behaviour in SSP command area pre Narmada and post Narmada. They observed a rising trend of water level across the command. They observed an increase in area under irrigation substantially, and maximum increase in the irrigated area through canal irrigation was found in Bharuch District. Farmers' dependence on wells and water purchase was reduced after the introduction of Narmada waters. Farmers allocated greater proportion of land to irrigated crops such as cotton (Bharuch), castor (Vadodara), and notable increase in the area under Kharif paddy, chick pea, wheat and maize in the area. Remarkable increase in crop yield was found for all crops especially, castor, cotton, paddy, and wheat in the command. This was due to, providing irrigation to Kharif crops which were earlier grown under rain-fed conditions, and farmers were growing longer duration high yielding varieties of crop, as they were assured of water for irrigation.

In view of the review of literature for SSP it is ample clear that there is need to undertake studies related to evapotranspiration and irrigation return in changing cropping pattern scenarios post Narmada water availability. Need is to examine the types of crops sown, quantity of water delivered to the crops, water consumed by evapotranspiration and irrigation seepage losses to assess the crop water requirement of major crops in various scenarios, impact and the effect of conjunctive use of surface and groundwater in the SSP region.

2.8 Concluding Remarks

In order to get a clear insight into the area of research, the investigator examined different literature from books, thesis, research works, reports, web sources and journals. Reviews were done from sources available, from Indian and foreign literature, and total of 133 reviews were selected relevant to the topic.

To match the irrigation supply with demand, estimation of the evapotranspiration is required to be done with appropriate methods, which can give reasonably good accuracy. Recent development in data acquisitions and techniques to model soil-water-crop interactions, require selection of appropriate model, and needs the understanding of capabilities and limitations of each available model. Various methods are available to estimate reference evapotranspiration based on climate data. FAO-PM is considered the sole standard method, in case all the climate data are available. Various methods to estimate crop evapotranspiration, from reference evapotranspiration are available using crop coefficient, and other approaches were reviewed here. The crop coefficient approach is widely used because of its simplicity. It is classified as single crop coefficient and dual crop coefficient. Amongst, the two crop coefficient approach, single and dual; the dual crop coefficient gives precise estimates of crop water requirement, especially during light and frequent wetting events. The dual crop coefficient approach, as it separates transpiration and evaporation, helps in estimating impacts of irrigation, or rainfall frequency on total crop water requirements. Soil moisture balance models give a helping hand to researchers, to monitor the soil water status, the inflow, outflow through the water lost, by

ET and deep percolation. Precisely estimating the transpiration or evaporation on days, following significant rainfall can help in irrigation scheduling on real time basis. As, water is becoming scarcer, the effects of climate change, resulting in moisture deficit in tropical regions are compelling the irrigation managers to resort to water saving technologies; there separate estimation of evaporation and transpiration, wherein dual crop coefficient approach is used could play an important role. Irrigation scheduling requires application of irrigation water at the proper time and of proper amount. Purpose of irrigation scheduling is to efficiently use the water, and assist the farmer in maximizing the crop yield. Various approaches which are employed for irrigation scheduling are transpiration ratio approach, soil moisture deficit approach, irrigation depth-interval-yield approach, water-balance accounting approach, critical stage approach, visual plant symptoms approach, and simulating evapotranspiration by models etc. The irrigation scheduling can be accomplished for full or partial crop water requirement. Deficit irrigation or partial crop water requirement is practiced, when there is water scarcity, or when irrigation system capacity is limited. Water use efficiency and irrigation water use efficiency maximize, when irrigation is applied according to soil water deficit. The most suitable strategy, for irrigation development is to use optimally the overall water of the area, including surface and groundwater over a period of time in a harmonious manner. Conjunctive use mitigates the problems of water logging, salinity, and facilitates the use of saline ground water by dilution with surface water. Various models for evaluating various irrigation strategies are available. However, with recent developments as discussed in this chapter, computing actual and potential ET for crop using Penman- Monteith with dual crop coefficient, coupled with FAO-56 Soil moisture balance method will enhance the overall results. Various studies are carried out in SSP region. It is for the first time, that the computations of actual and potential ET for crop using Penman-Monteith with dual crop coefficient, coupled with FAO-56 Soil moisture balance method is being done, for 16 blocks of region I and 4 blocks of region II, of SSP for major fourteen crops. This may add a new dimension for decision making for irrigation managers, and help in evaluating various irrigation strategies. Next chapter deals with the theoretical aspects of the study, adopted for the present study.