Chapter 3

Theoretical Aspects of the Study

3.1 General

Determining the crop water requirements few years back was a tedious work, as it required matching the irrigation supply with crop water demand. Crops water requirement is different throughout the growing period, due to variation in crop canopy and climatic conditions (Allen et al., 1998). The amount of water required to (indemnify) secure, against loss of the evapotranspiration from the cropped field, is defined as crop water requirement. Crops require a fixed quantity of water to meet the water losses, through evapotranspiration from precipitation / irrigation, for bumper crop production under pristine conditions. Complexities involved in estimating evapotranspiration with various parameters involved, make it a challenging task, for proper estimation of evapotranspiration with appropriate methods. With the advent of latest automatic weather station, the data is easily available in hourly as well as daily time step, thereby enabling the users to compute reference evapotranspiration, by latest empirical equations.

3.2 Reference Evapotranspiration

Crop evapotranspiration can be computed by multiplying reference crop evapotranspiration to crop coefficient. Grass / Alfalfa are generally taken as reference crop. The reference crop evapotranspiration can be estimated by many methods. The FAO Penman-Monteith method is recommended as sole standard method, for the definition and computation of the reference evapotranspiration, especially when there is availability of data, amongst large number of empirical and semi empirical equations (Allen et al., 1998). FAO-56 Penman-Monteith equation (3.1) is denoted as follows:

$$ET_o = \frac{o.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad (3.1)$$

Where, ET_o= reference evapotranspiration, (mm.day^{-1}), R_n=net radiation at the crop surface, (MJm^{-2}.day^{-1}), G = soil heat flux density, (MJm^{-2}.day^{-1}), T = mean daily air temperature at 2m height, (°C), u_2 = wind speed at 2m height, (ms^{-1}), e_s = saturation vapour pressure, (k Pa), e_a = actual vapour pressure, (k Pa), $e_s - e_a$ = saturation vapour pressure deficit, (k Pa), Δ = slope vapour pressure deficit, (k Pa °C^{-1}), and γ = psychometric constant (k Pa °C^{-1}).

3.3 Dual Crop Coefficient Approach

The crop coefficient is generally used to find out precisely the actual water needs of the field crop. It is the ratio of crop evapotranspiration ET_c to reference crop evapotranspiration ET_o (Equation 3.1).The effect of crop characteristics differentiating a field crop, from the reference crop (grass) is integrated with help of crop coefficient K_c value. All crops will have different crop coefficients. The values of K_c are dependent and influenced by changing crop characteristics, under various stages of growth. The factors influencing crop coefficient (K_c) are, (i) Crop type, (ii) Climate, (iii) Soil evaporation, and (iv.) growth stage of crop. In crop coefficient approach the crop evapotranspiration, ET_c, is estimated by multiplying crop coefficient to reference crop evapotranspiration, denoted in equation 3.2. (Allen et al., 1998)

$$ET_c = K_c \times ET_o \tag{3.2}$$

There are two approaches to determine the crop coefficient K_c. (1) Single Crop Coefficient, and (2) Dual Crop Coefficient (Allen et al., 1998). The crop coefficient expresses the difference in evapotranspiration, between the reference grass surface and the field crop. The difference can be incorporated into one single coefficient, or it can be broken up into two factors, describing separately the difference in evaporation and transpiration between both surfaces.

In single crop coefficient approach, the effects of soil evaporation and crop evapotranspiration are combined into one K_c coefficient. Dual crop coefficient approach, calculates the actual increase in K_c for each day as a function of plant development, and the wetness of the soil surface. Further, the effects of soil evaporation and crop evapotranspiration are calculated separately. Instead of one coefficient, it uses two coefficients, (1) Basal crop coefficient describing crop transpiration, and (2) Soil water evaporation coefficient which describes the soil water evaporation from the soil surface (Allen et al., 1998).

The single crop coefficient K_c is substituted, by the following equation 3.3

$$K_c = K_{cb} + K_e \tag{3.3}$$

The basal crop coefficient K_{cb} is defined, as the ratio of crop evapotranspiration (ET_c) to reference evapotranspiration (ET_o or ET_{ref}). It represents the condition when soil surface layer is dry, but average soil moisture content in the root zone is sufficient to support full transpiration of plant. The soil water evaporation coefficient K_e, determines the soil water evaporation from soil surface. Soil evaporation coefficient K_e (equation 3.4) is calculated when the topsoil dries out, and evaporation is less, and evaporation reduces in proportion to the amount of water available in surface soil layer (Allen et al., 1998, Allen R. G. 2002 and Allen et al., 2005).

$$K_e = min\ (K_r \times (K_{c\ max} - K_{cb}),\ f_{ew} \times K_{c\ max}) \tag{3.4}$$

Where, K_e = soil evaporation coefficient, $K_{c\ max}$ = the maximum value of K_c following rain or irrigation, K_r = evaporation reduction coefficient and is dependent on the cumulative depth of evaporated water, and f_{ew} = the fraction of the soil that is both exposed to solar radiation and that is wetted.

The evaporation rate is restricted by the estimated amount of energy available at the exposed soil fraction, i.e. K_e cannot exceed $f_{ew} \times K_{c\ max}$. The calculation procedure consists in determining the following: (i) The upper limit of $K_{c\ max}$; (ii) the exposed and wetted soil fraction f_{ew}; and (iii) the soil evaporation reduction coefficient K_r;

Upper limit ($K_{c\ max}$) is denoted by equation 3.5 (Allen et al., 1998).

$$K_{c\ max} = \max\ (1.2 + [0.04(u_2 - 2) - 0.004(RH_{\ min} - 45)]\ (\frac{h}{3})^{\ 0.3};\quad K_{cb} + 0.05) \tag{3.5}$$

Where, u_2 = wind speed measured at 2m height in m/s, $RH_{\ min}$ = minimum relative humidity in %, h = plant height during the current day in meter.

The equation 3.5 ensures that $K_{c\ max}$ is always greater than or equal to the sum K_{cb} + 0.05, suggesting that the wet soil increase the K_c value by 0.05, following complete wetting of the soil surface, even during periods of full ground cover.

3.3.1 Exposed and Wetted Soil Fraction (f_{ew})

Exposed and wetted soil fraction (f_{ew}) defines the potential spatial extent of evaporation. When the soil surface is completely wetted in case of precipitation, or irrigation, f_{ew} are set equal to (1-f_c). For irrigation systems, where only a fraction of the ground surface (f_w) is wetted e.g. furrow, f_{ew} are limited to f_w. Both (1-f_c) and f_w, for numerical stability, have limits [0.01-1]. Exposed and wetted soil fraction (f_{ew}) is calculated as shown in equation 3.6 (Allen et al., 1998).

$$f_{ew} = \min\ (1 - f_c,\ f_w) \tag{3.6}$$

Where, f_c = fraction of soil surface effectively covered by vegetation, f_w = fraction of the surface wetted by irrigation and/or precipitation.

3.3.2 Soil Fraction Covered by Vegetation (f_c)

Soil fraction covered by vegetation (f_c) value will change daily as K_{cb} changes. $K_{c\ min}$ has the same value as $K_{cb\ ini}$ (i.e. $K_{c\ min}$ = 0.15). The difference $K_{cb} - K_{c\ min}$ is limited to ≥ 0.01 for numerical stability. The value for f_c ranges between 0 and 0.09 for numerical stability. Soil fraction covered by vegetation (f_c) can be estimated from K_{cb} by equation 3.7 (Allen et al., 1998).

$$f_c = \left(\frac{K_{cb} - K_{c\,min}}{K_{c\,max} - K_{c\,min}}\right)^{(1+0.5\,h)} \tag{3.7}$$

Where, $K_{c\ min}$ = the minimum K_c for dry bare soil with no ground cover, h = plant height during the current day in m.

When soil is wet, following rain or irrigation the value of K_e is large. The value of K_e diminishes and reaches zero, when no water is left for evaporation as the soil surface dries subsequently. In no case, the sum of K_{cb} and K_e should exceed the maximum value, K_c max; which is decided by the energy available for the evapotranspiration at the soil surface.

3.3.3 Soil Evaporation Reduction Coefficient (K_r)

Soil evaporation from the exposed soil can be assumed to take place in two stages: an energy limiting stage, and a falling stage. When the soil surface is wet, K_r is 1, when the water content in the upper soil becomes limiting, K_r decreases. K_r becomes zero when the total amount of water that can be evaporated i.e. total evaporable water (*TEW*), from the top soil is depleted. Readily evaporable water (*REW*) is the water content that can be evaporated in the first stage (energy limiting). The total amount of water that can be evaporated in a complete drying cycle is estimated and denoted by equation 3.8 (Allen et al., 1998).

$$TEW = 10 \times (\theta_{FC} - 0.5\,\theta_{WP}) \times Z_e \tag{3.8}$$

Where, *TEW* = total evaporable water, the maximum depth of water that can be evaporated from the surface soil layer, assuming that the soil was completely wetted, in mm, θ_{FC} = field capacity in % volume, θ_{WP} = wilt point in % volume, and Z_e = the effective depth of the surface soil, subject to drying to 0.5 θ_{WP} by way of evaporation in m. Z_e is an empirical value based on observation, a fixed value of 0.08m, which has been used in MABIA method.

The readily evaporable water (*REW*) is the maximum depth of water that can be evaporated, from the top soil layer without restriction is denoted in equation 3.9 (Allen et al., 1998).

$REW = (3.121 \times TEW + 22.896) \times Z_e$ (3.9)

The soil evaporation reduction coefficient (K_r) is estimated as per equation 3.10 (Allen et al., 1998).

$$K_r = 1, \quad \text{for } D_{e,i-1} \leq REW \text{ and}$$

$$K_r = (TEW - D_{e,i-1}) / (TEW - REW), \quad \text{for } D_{e,i-1} > REW \qquad (3.10)$$

Where, TEW = total evaporable water in mm, $D_{e,i-1}$ = cumulative depletion from soil surface layer at the end of day i-1(the previous day) in mm, and REW = readily evaporable water in mm. The soil evaporation reduction coefficient K_r value maximizes when soil is wet, and evaporation occurs at potential rate. The value of K_r equal's unity, following rainfall or irrigation. As the soil surface dries, actual evaporation begins to decline below the potential rate $K_r < 1$. When no water is available for evaporation in the top soil, then K_r reaches zero. Evaporation from the soil beneath the crop canopy occurring at a slower rate is assumed included in the basal crop coefficient K_{cb}.

3.3.4 Water Balance of the Soil Surface Layer

Estimation of evaporation coefficient, requires a daily water balance for the f_{ew} fraction of the surface soil layer, Water balance of the soil surface layer is expressed in terms of depletion at the end of the day, is denoted in equation 3.11 (Allen et al., 1998).

$$D_{e,i} = D_{e,i-1} - (P_i - RO_i) - \frac{I_i}{f_w} - \frac{E_i}{f_{ew}} + T_{e,i} + DP_{e,i} \qquad (3.11)$$

Where, $D_{e,i}$ = cumulative depletion depth at the end of day i in mm, $D_{e,i-1}$ = cumulative depletion depth at the end of the previous day, i-$_1$ in mm, P_i and RO_i = precipitation and precipitation runoff from the soil surface on day i in mm, I_i = irrigation depth on day i that infiltrates the soil in mm, E_i = evaporation on day i ($E_i = K_e \times ET_o$) in mm, $T_{e,i}$ = the depth of transpiration from the exposed and wetted fraction of the soil surface layer on day i in mm, and $DP_{e,i}$ = deep percolation from the f_{ew} fraction of the soil surface layer on day i if soil water content exceeds the field capacity in mm .

Assumption taken here is that surface layer is at field capacity, following heavy rainfall, or irrigation. The limits imposed on $D_{e,i}$ are as follows $0 \leq D_{e,i} \leq TEW$

The dual crop coefficient approach (K_{cb} + K_e) gives a better estimation of daily crop evapotranspiration, because it separately considers soil evaporation and crop transpiration.

Numerical determination of K_{cb} can be obtained as described in FAO 56. Dual crop coefficient approach allows one to plan irrigation schedules properly, especially in the case of crops that do not completely cover the soil, where evaporation from the soil surface may be substantial (Rosa et al., 2012).

Due to more complexities involved than the one time averaged K_c coefficient (i.e. single crop coefficient) the dual coefficient approach is best suited for research studies, real time irrigation scheduling, and for soil moisture balance computations; where daily variations in soil surface wetness, soil moisture profile, and continuous changing deep percolation, play a vital role (Allen et al., 1998; Rosa et al., 2012; and Bhatti and Patel, 2012)

The selection of the approach primarily depends upon the availability of climatic data, accuracy required and the purpose of the calculation. After selecting and adopting any one approach the calculation procedure for the crop evapotranspiration be carried out as follows: (1) Determining the lengths of the crop growth stages and their corresponding crop coefficient. (2) Adjusting the selected K_c coefficients for the wetting frequency of soil surface, and/or the local climatic conditions during the growth stages. (3) Construct crop coefficient curve. (4) Determining the daily values of K_e, for surface evaporation only in case of dual crop coefficient approach. (5) Crop evapotranspiration ET_c is computed, by multiplying Reference Evapotranspiration (ET_o or ET_{ref}) by Crop coefficient (K_c). The dual crop coefficient is adopted in this study and crop evapotranspiration is computed under standard conditions (ET_c) i.e. ($ET_c = (K_{cb} + K_e) \times ET_o$) and non standard conditions (ET_{cadj} or ET_a) discussed below.

3.4 Water Stress Coefficient (K_s)

Under pristine conditions the crop evapotranspiration is at potential rate, but under soil moisture stress due to limited soil moisture availability, the actual evapotranspiration (transpiration and evaporation) is less than the potential value. The stress factor is estimated in terms of the readily and total available water parameters, which depend on soil properties and the effective depth of the roots. The effect of soil water stress is incorporated by multiplying the crop coefficient by the water stress coefficient K_s. Actual crop evapotranspiration computed using the dual crop coefficient approach is denoted in equation 3.12 (Allen et al., 1998).

$$ET_a = (K_s \times K_{cb} + K_e) \times ET_o \tag{3.12}$$

Where there is no soil water stress, $K_s = 1$, while for soil water limiting conditions, $K_s < 1$.

To avoid crop water stress irrigation is needed to be applied. The K_s value can be calculated as mentioned below in equation 3.13 (Allen et al., 1998 and Allen 2002).

$$K_s = 1, \qquad \text{for } D_r \leq RAW$$

$$K_s = (TAW - D_r) / (TAW - RAW), \qquad \text{for } D_r > RAW \tag{3.13}$$

Where TAW = total available water in mm, D_r = root zone depletion in mm, and RAW= readily available water in mm.

TAW is estimated as the difference between the water content at field capacity and wilting point in % of volume denoted in equation 3.14 (Allen et al., 1998).

$$TAW = 10 \times (\theta_{FC} - \theta_{WP}) \times Z_r \tag{3.14}$$

Where, Z_r = the effective rooting depth in m. For stage 1, $Z_r = Z_{r\,min}$, for stage 3 and 4,

$Z_r = Z_{r\,max}$, for stage 2, Z_r is estimated as per equation 3.15 (Allen et al., 1998).

$$Z_r = \left(\frac{K_{cb\,i} - K_{cb\,ini}}{K_{cb\,mid} - K_{cb\,ini}}\right)(Z_{r\,max} - \mathrm{Z}_{\mathrm{r\,min}}) + \mathrm{Z}_{\mathrm{r\,min}} \tag{3.15}$$

Where, $Z_{r\,max}$ = maximum rooting depth for crop in m, $Z_{r\,min}$ = minimum rooting depth for crop in meter.

RAW is estimated as per equation 3.16 (Allen et al., 1998).

$$RAW = p \times TAW \tag{3.16}$$

Where, p is depletion factor, which varies by crop and crop growth stage, and typically ranges between 0.4 for shallow rooted crops to 0.6 for deep rooted crops. The depletion factor p, maximum rooting depth $Z_{r\,max}$, the water content at field capacity θ_{FC} and wilting point θ_{WP} in % of volume is taken as input data in WEAP-MABIA model.

Water stress coefficient K_s value maximizes when soil is wet, and evapotranspiration occurs at potential rate. The value of K_s equal's unity, following rainfall, or irrigation. As the soil surface dries, actual evapotranspiration begins to decline below the potential rate $K_s < 1$. When no water is available for evapotranspiration in the top soil, then K_s reaches zero. The crop is said to be water stressed when the soil starts drying and potential energy of the soil water drops below a threshold value. In conventional practices, the irrigation is applied before the stress conditions are attained, if there is no rainfall. If soil moisture deficit exist and there is substantial rainfall, the moisture is retained near the soil surface; this is most obvious when the soil has an appreciable clay content. After significant rainfall, the soil remains moist near the ground surface and crop continue to revive for several days. The value of soil moisture depletion (*SMD*) with respect to total evaporable water (*TEW*), total available water (*TAW*), readily evaporable water (*REW*), and readily available water (RAW) can be classified in three situations.

(1) $REW / RAW \geq SMD$ (The crop will have potential evaporation and evapotranspiration).

(2) $TEW/TAW > SMD \geq REW / RAW$ (The crop will have reduced evaporation and evapotranspiration).

(3) $SMD > TEW / TAW$ (The crop will have no evaporation and no evapotranspiration).

The distribution of moisture in the soil is not so important in the first situation, since the actual evapotranspiration equals the potential value. In situation (2) and (3), crop stress coefficient (K_s), and soil evaporation coefficient (K_e) are required to be introduced, for consideration of reduced soil moisture (Rushton et al., 2006). To avoid crop water stress, irrigation needs to be applied before, or at the moment, when readily available water (*RAW*) is equal, or greater than soil moisture depletion (*SMD*) i.e. $SMD < RAW$. However, management induced soil water stress may be initiated in different growth stages, for crops like cotton, sugar beet, coffee etc. to have better yield (FAO 1998).

3.5 Crop Yield Response Factor (K_y)

Crop production is dependent mainly on soil water status, throughout the growing season. Optimal yield is ensured with high level of soil water availability with maximum actual evapotranspiration however, with potential water losses due to percolation. 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 (Doorenbos and Kassam, 1979).The experiments worldwide have proved that the highest crop productivity can be achieved with optimum water supply. The water stress condition is created when water supply to crops from rainfall/irrigation is below the optimal level, which affects the crop growth and productivity. Mannocchi and Mecarelli (1994) stated it was feasible to model relationship between crop yield and water applied, by using crop yield response factor equation. Seasonal, or crop growth stage sensitivity, and crop tolerance to water stress is indicated with crop yield response factor $K_{y.}$ The response of crop yield to water supply is quantified by the yield response factor K_y in FAO 56. Crop yield response factor, estimates relative yield reductions based on the measured reduction in crop transpiration (Moutonnet

2002). The crop yield response factor K_y, varies depending on species, variety, irrigation method and management, and growth stage, when deficit evapotranspiration is imposed. The crop yield response factor is denoted in equation 3.17 (Sieber and Purkey, 2011).

$$\mathrm{K_y} = [1 - \frac{\mathrm{Y_a}}{\mathrm{Y_m}}] \Big/ [1 - \frac{\mathrm{ET_a}}{\mathrm{ET_c}}] \tag{3.17}$$

The relative yield fraction is denoted by equation 3.18 (Sieber and Purkey, 2011).

$$\frac{Y_a}{Y_m} = \left[1 - K_y\left(1 - \frac{ET_a}{ET_c}\right)\right] \tag{3.18}$$

Where, $\mathrm{Y_a}$ and $\mathrm{Y_m}$ are actual and maximum crop yields, corresponding to actual evapotranspiration ET_a and maximum evapotranspiration ET_c.

If a crop response factor is greater than unity, it indicates that the relative yield decrease for a given evapotranspiration deficit is proportionately greater than the relative decrease in evapotranspiration. Thus 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 (Kirda et al., 1999a).

Several crops respond differently, according to degrees of drought tolerance, during period of water stress, while certain crops get accustomed to water stress conditions, under limited water supply and have better yields even with less water. Precise knowledge of crop response to water is must as drought tolerance varies, as per growth stage and crop species (Doorenbos and Kasam, 1979). 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 (Kirda, 2002).

The water stress in the crops is not constant throughout the growth period, but occurs in different magnitude at different growth stages. It is necessary to compute relative yield fraction at smaller time step i.e. daily, and multiplicative product of the yield fraction of all days should be used as relative yield fraction for the season (equation 3.19) (Raes et al., 2006 and Sieber & Purkey, 2011).

In MABIA method relative yield fractions is calculated on daily time step, and aggregated for the season is useful in estimating the yield accurately.

$$1 - K_y\left(1 - \frac{ET_a}{ET_c}\right) = \prod_{i=1}^{N}[1 - K_{y,s}\left(1 - \frac{ET_{a,i}}{ET_{c,i}}\right)]^{1/L_s} \qquad (3.19)$$

Where, Π indicates the product of the N terms within the square brackets, N = length of growing season [days], i = day number within the growing season [1….N], s = crop stage corresponding to day I [1-4], $K_{y,s}$ =yield response factor for crop stage/ s, from the crop library, L_s = length of crop stage/ s, $ET_{a,i}$ = actual evapotranspiration at day i, and $ET_{c,i}$ = potential evapotranspiration at day i.

To obtain actual yield equation 3.20, multiply the seasonal relative yield fraction (equation 15) by maximum theoretical yield (Sieber and Purkey, 2011).

$$Y_a = Y_m\left[1 - K_y\left(1 - \frac{ET_a}{ET_c}\right)\right] \qquad (3.20)$$

Under water stress condition, the soil moisture depletion may reduce below total available water. Under this condition, the daily yield fraction tends to zero. It has been observed that in daily time step, if daily yield fraction is zero, during any growing stage the yield is deduced to be zero during the season. To ensure optimal yield monitoring of crop water use and irrigation water use is must.

3.6 Water Use Efficiency and Irrigation Water Use Efficiency

Water being finite resource for which there is growing demand amongst, agriculture, industries, and domestic use, under growing population. Thus, need of an hour is to maximize crop yields, under conditions of limited water supply. Crop water productivity or water use efficiency (WUE) of crop is computed as yield per crop evapotranspiration.

Smith et al., (2002) reported that the water stress results in less evapotranspiration, by closure of the stomata, thereby resulting in reduced absorption of carbon and decreased biomass production. WUE is a biological indicator wherein; the water stress affects the crop growth and productivity. Any restriction in the supply of water is likely to induce a decrease in evapotranspiration, thereby resulting in decrease in WUE. Water use efficiency (WUE) is computed, as yield of crop per actual evapotranspiration. The maximum water use efficiency (WUE) tends to occur at maximum ET (ET_c). Water use efficiency WUE or (E_c) is given in equation 3.21 (Kirda 2002 and Oweis et al., 2011).

$$E_c = \frac{Y}{ET_a} = \left[K_y - \frac{K_y - 1}{\frac{ET_a}{ET_c}}\right] \times \frac{Y_m}{ET_c} \qquad (3.21)$$

Success of any irrigation system lies primarily to obtain optimal yield per drop of water, which can be derived with Irrigation water use efficiency (IWUE) of crop. Irrigation water productivity or irrigation water use (IWUE) is influenced by performance of irrigation system, and degree of losses beyond transpiration, which is estimated from yield per irrigation water applied, denoted by equation 3.22 (Oweis et al., 2011).

$$IWUE = \frac{Y_a}{I} \qquad (3.22)$$

Where, IWUE = Irrigation water use efficiency, Y_a = actual yield in kg, and I = irrigation water applied in mm.

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

Tolk et al., (2003) observed that generally IWUE declined with increasing irrigation application, 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. Howell et al., (1995) showed that both maximum WUE and IWUE occurred at, or near ET_c, which had high rainfall and somewhat cooler season than normal. But, when the climate was more typical of the region, both maximum WUE and IWUE occurred at an ET considerably less than ET_c. In general experiments have demonstrated that WUE decrease with reduction in irrigation water application, while the IWUE increase with decrease in irrigation water application, due to greater utilization of stored soil water at higher deficits. The effective precipitation estimated by SCS method, if taken as an input in soil moisture balance can be of great help for computing crop water requirements precisely

3.7 SCS Method for Calculating Effective Precipitation

After the commencement of rainfall the soil can store fraction of the rainfall within the root zone of the soil. Out of the total rainfall, part of it flows as surface run off, percolates into ground, evaporates back, and does not contribute to the available soil moisture for the crop. Thus, effective precipitation is only that part of the precipitation, which contributes to the soil moisture available for plants. Actual water availability to the crop is rainfall minus runoff, evapotranspiration, and deep percolation. The Curve Number Method developed by the Soil Conservation Service (Soil Conservation Service 1964 and 1972 U.S.A) can be used to estimate the depth of direct runoff from the rainfall.

It is observed that in small basins, runoff starts only after certain rainfall gets accumulated post high intensity rainfall, and that the curves asymptotically approach a straight line with a 45-degree slope when plotted. The fundamentals of curve number method depend on three basic processes, which occur during rainfall. (1) Initial abstraction: It is primarily the accumulation of rainfall prior to start of runoff, and it involves interception, depression storage, and infiltration. (2) Actual retention: It is mainly in form of infiltration, which occurs after starting of runoff, and some of the additional rainfall is lost. (3) Potential maximum retention: It is the increase in actual retention with increasing rainfall up to the maximum value. This empirical relationship of rainfall and runoff can be denoted, by equation 3.23 in mathematical form as follows:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \qquad (3.23)$$

Where, Q = accumulated runoff depth (mm), P = accumulated rainfall depth (mm), I_a, = initial abstraction (mm), and S = potential maximum retention (mm).

To eliminate the need to estimate the two variables I_a, and S through regression analysis of recorded rainfall, and runoff, following average relationship is used I_a = 0.2 S. The potential maximum retention S is converted to the Curve Number CN, in order to make the operations of interpolating, averaging, and weighting more nearly linear, and relationship between the two is denoted by equation 3.24.

$$S = (25400/\ CN) - 254 \qquad (3.24)$$

The curve number value of cultivated agriculture lands is available in Natural resource conservation Service (NRCS 1985). The curve number value is influenced by antecedent moisture conditions, hydrologic soil groups, cover type, and hydrologic conditions. Dry, average and wet antecedent moisture conditions (AMC) exist in any of the sub basins. Antecedent moisture conditions is considered to be low (refer equation 3.25), when there has been little preceding rainfall, and high (refer equation 3.26), when there has been considerable preceding rainfall prior to modelled rainfall event. For modelling purposes five day antecedent rainfalls average moisture conditions are required to be considered, that is AMC (II).

Runoff curves numbers (RCN) need to be adjusted for differing antecedent moisture conditions based upon equations given below:

$$RCN\ (I) = (4.2\ RCN\ (II)) / (10 - 0.058\ RCN\ (II)) \qquad (3.25)$$

$$RCN\ (III) = (23\ RCN\ (II)) / (10 + 0.13\ RCN\ (II)) \qquad (3.26)$$

The curve number differs in accordance to hydrologic soil groups A, B, C, D which needs to be correctly selected and incorporated in the equations. The effective precipitation estimated separately by SCS method is taken as an input for calculating crop water requirements. The estimation of evapotranspiration, and crop water requirement was carried out in EXCEL; but as the data sets are huge, the estimation of evapotranspiration, and crop water requirements, for various major crops, for the study area has been carried out by using MABIA based WEAP model. Soil-crop-water interaction and its effects can be determined using soil moisture balance techniques.

3.8 Soil Moisture Balance and Use of WEAP Model

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 (Rao, 1987). Crop water requirement can be determined by estimating evapotranspiration, by root zone water balance using different methods like gravimetric, neutron scattering, capacitance and time domain reflectometry etc. However, typical problems are also associated with these methods in estimating ET accurately. Adopting a reliable soil water balance simulation model can be helpful in identifying and overcoming the difficulties faced in estimating ET from soil water observations by comparative study (Allen et al., 2011). Crop water requirements can be estimated, by calculating the soil water balance of the root zone on daily basis. This will help in planning the timing and depth of irrigation.

In an attempt to obtain more yield the farm managers sometimes over irrigate, which lead to salinity and water logging problems. Monitoring of water balance in irrigation schemes is advocated worldwide to check groundwater rise. After significant rainfall/ irrigation a soil becomes free draining, when the moisture content of the soil reaches a limiting value called the field capacity; excess water then drains through the soil to become recharge. To determine when the soil reaches this critical condition it is necessary to simulate soil moisture conditions on a daily basis throughout the year (Rushton et al., 2006).

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 balance approach to find the storage index. Computer models can be of great help to estimate the soil water balance, and for developing and evaluating various irrigation strategies (Prats and Pico, 2010).

Models are developed recently to compute water demands, by routing the root zone moisture in an integrated hydrology. Soil moisture balance in root zone is 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 (Dogrul et al., 2011).

Many computer programs related to soil moisture are available, which help to decide whether to irrigate, or not according to pedological, agricultural and meteorological parameters. Nowadays, it is possible to monitor soil moisture status in varied soils, using soil moisture balance techniques with help of computer models, and generating improved irrigation schedules. These models are right tools for developing and evaluating irrigation strategies.

Various water balance models have been developed based on well recognized methodologies, for determination of crop evapotranspiration and yield responses to water with simulation of crop water stress conditions, and computation of yield reductions (FAO 1998 and FAO 1979). CROPWAT model (FAO 1992) is widely used for this purpose which uses single crop coefficient. WEAP model has incorporated MABIA method, which provides daily simulation of transpiration, evaporation, irrigation requirements and scheduling, crop growth, and yields. It includes modules for estimating reference evapotranspiration and soil water capacity. It uses dual Kc method as described in FAO-56. MABIA is an improvement over CROPWAT, which uses dual crop coefficient approach separating evaporation and transpiration (Sieber and Purkey, 2011). Amongst, the available computer models WEAP-MABIA is a useful tool, to compute actual evapotranspiration and soil moisture balance on daily basis (Sieber and Purkey 2011and Choksi et al., 2012). A daily water balance, expressed in terms of depletion at the end of the day, is denoted in equation (3.27) (Allen et al., 1998):

$$D_{r,i} = D_{r,i-1} - P_i + SR_i - I_i - CR_i + ET_{a,i} + DP_i \tag{3.27}$$

Where $D_{r,i}$ = root zone depletion at the end of day i [mm], $D_{r,i-1}$ = depletion in the root zone at the end of the previous day, i_{-1} [mm], P_i = precipitation on day i [mm], limited by maximum daily infiltration rate [mm], SR_i = surface runoff from the soil surface on day i [mm], I_i = net irrigation depth on day i that infiltrates the soil [mm], CR_i = capillary rise from the groundwater table on day i [mm], $ET_{a,i}$ = actual crop evapotranspiration on day i [mm], and DP_i = water flux out of the root zone by deep percolation on day i [mm] .

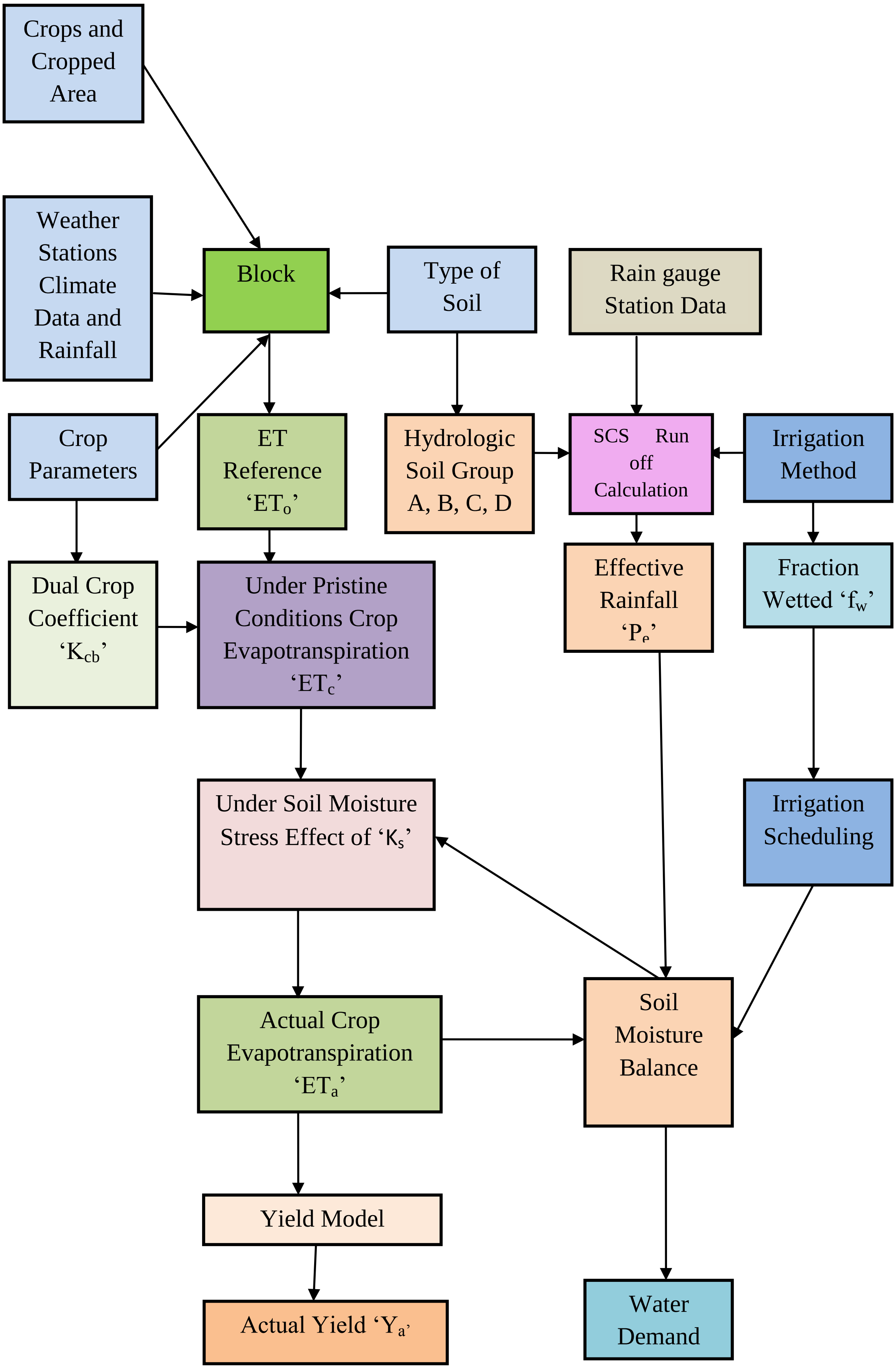

Figure 3.1: Flowchart of methodology

The daily moisture balance equation (3.27) enables the user to simulate various irrigation scenarios, and estimate yield reductions, if any. The effective precipitation estimated by SCS method, and taken as an input in soil moisture balance can be of great help, for computing crop water requirements precisely. Information system model integrated with WEAP will assist the planners in monitoring and taking suitable decisions, for computing crop water requirements for management of irrigation water demand. Flowchart of methodology is shown in Figure 3.1. To meet the crop water requirements during deficit soil moisture conditions, irrigation needs to be applied. Conventional irrigation strategies result in either over irrigation causing water losses, or water stress condition leading to yield reduction. To optimize yield, and water savings, evaluating irrigation strategies is needed.

3.9 Evaluating Irrigation Strategies

The prevalent irrigation scheduling strategies adopted worldwide have been discussed in earlier chapter. Under limited water supply conditions it would not be rationale to stick to traditional practices to maximize irrigation, for maximum productivity, but opt for different irrigation scheduling. It is not necessary maximum yield, or highest water productivity, or net profit be achieved by maximum irrigation; rather investigations have proved that highest crop water productivity matched with lesser irrigation amounts than the full crop water requirements. In view, of this various irrigation scheduling needs to be evaluated, and depending upon the goals to be achieved, the suitable irrigation strategies needs to be suggested, and incorporated in Sardar Sarovar region I and II. To know the effectiveness of selected strategies, and to find the best suited irrigation strategy, amongst them in accordance to the prevailing scenarios, need is to compare and examine the selected strategy with a standard irrigation strategy. No stress condition strategy with optimum irrigation water (denoted as strategy S III in next chapter), would provide maximum potential yield with significant savings of water. Thus comparison of yields of selected strategy with standard strategy can be done and percentage change in yield can be denoted by equation (3.28). While, comparison of irrigation of selected strategy with standard strategy can be done and percentage change in irrigation can be calculated and denoted by equation 3.29.

Percentage change in yield =100 × (Yield of selected Strategy – Yield of Strategy S III) / (Yield of Strategy S III) (3.28)

Percentage change in irrigation depth =100 × (Irrigation depth of selected Strategy – Irrigation depth of Strategy S III) / (Irrigation depth of Strategy S III). (3.29)

After evaluating the irrigation strategies, the best strategy amongst them, requires to be identified from yield point of view; wherein statistical tool would be very useful.

3.10 Statistical Analysis

The primary objective of the study is to identify the best irrigation strategy in study area of agro-climatic region I and II. To irrigate the large area with ease agro-climatic regions I and II are divided into number of blocks with varying areas by SSNNL authorities. Due to vastness of the study area it is difficult to conduct real life experiment, and obtain the data in a short span of time to undertake the study. In such situation, simulated experimental tool is used to generate the data of yield, for different irrigation strategies over different types of blocks.

The controllable parameters are date of sowing, type of crop, type of soil, and crop parameters, which are maintained and controlled using WEAP-MABIA model.

Design of experiment is a very powerful tool of applied statistics, to study and compare the impact of set of treatments, and conclude more precisely. The basic principles of design of experiments are replication, randomization, and local control (i.e. principles of blocking). It uses a tool called analysis of variance (ANOVA). Here Randomized block design (RBD) is used as a tool, to study and compare impact of different irrigation strategies, to recommend the best one, and otherwise. Analysis of variance and randomized block design (RBD) are briefly described below. A method of multiple comparisons of irrigation strategies is done, if their effect is significant, it is also discussed. This is available in all standard books on design of experiments.

3.10.1 Analysis of Variance

Analysis of variance is employed, when observations from an experiment pertaining to yield, or measurement of any character, vary from each other greatly. This variation may be due to number of factors known as source of variation, and the portions of variation caused by different sources are known as components of variation. The statistical analysis aims at assessing this total variation present, and apportioning it between the various factors responsible for the same. The analysis of variance is a simple arithmetical process of sorting out the components of variation in a given data. Fisher quotes ‘It is a tool by which the total variation may be split up into several physically assignable components’. Analysis of variance plays a dual role. First it sorts and estimates the variance components, and secondly it provides for the test of significance' (Chandel, 1998).

3.10.2 Randomized Block Design

In randomized block design the whole experimental material is divided into homogeneous groups, each of which constitutes a single replication. Each of these groups is further divided into number of experimental units, which are equal in all respects. Treatments are applied to these units by any random process. In case of field experiments, if it is observed that the fertility gradient of the field is one direction, the whole field may be divided into number of equal plots. The number of plots in each block is equal to the number of treatments, so that each block is a replicate of each treatment.

Chandel (1998) suggested that following important points should be kept in mind for RBD. (1) In this design the number of blocks must be equal to number of replications fixed for each treatment. (2) The number of plots in each block should be equal to the number of treatments. (3) Experimental errors within each block are to be kept as small as possible and the variation from block to block as great as possible. In this way all the treatments which are assigned to one block, experience the same type of the environmental effects, and are therefore comparable. (4) Randomization of treatments in each block should be afresh.

Randomized Block Design RBD as a tool evaluates, differences among more than two groups that contain matched samples, or repeated measures that have been placed in blocks. In RBD blocks are heterogeneous sets of items or individuals that on whom measurements have been taken. Blocking removes as much variability as possible from the random error, so that the differences among the groups are more evident. Although blocks are used in a randomized block design, the focus of the analysis is on the differences among the different groups. (Gupta, 2010; RBD, 2011)

Data of yield for different irrigation strategies can be analyzed as Randomized Block Design (RBD) without replication using Microsoft Excel. To find appropriate irrigation strategy/ strategies for each crop with a RBD of statistical design of experiments, RBD ANOVA for each crop requires, testing the following null hypothesis:

$H_{0\ 1n}$: For each crop, irrigation strategies have similar effect

$H_{0\ 2n}$: For each crop, block effects are similar

Against H_0 following alternatives are

$H_{1\ 1a}$: Effects of irrigation strategies differ significantly (i.e. strategies are not equally effective).

$H_{1\ 2a}$: Blocks are not homogeneous, and there is significant difference between their effects.

ANOVA uses F test which requires calculation of F value, and obtaining (available in statistical tables as well as in Excel) F *critical* for 5% and 1% level of significance. If F value is less than F *critical* for 5% level of significance, then the test is insignificant, which means that there is no significant difference in the effect of treatment/strategies in the study under taken. In that situation we may accept null hypothesis. If F > F *critical* for 5% level of significance then test is significant (denoted by *). If F > F *critical* for 1% level of significance then test is highly significant (denoted by **). In this case we reject null hypothesis and accept alternative hypothesis.

In order to decide which strategy is best, they are placed in order of the best, and then **multiple comparisons** are carried out by computing Standard Error (SE) (refer equation 3.30) and Critical Difference (CD) (refer equation 3.31) as follows:

1. $SE = \sqrt{(2MSE/r)}$ (3.30)

   Where, MSE = Mean Square Error, r = No. of replications = No. of Strategies = Strategies df + 1

2. $CD = SE \times t_\alpha$ (3.31)

   Where, t_α = Error degree of freedom (available in statistical tables, $\alpha = 0.05$ level of significance).

3. To place them in order of best, average effect of treatments (over here irrigation strategies), and arrange them in descending order of magnitude.

Select any consecutive pair of treatments, and find difference in their average effect. If this difference is greater than CD, it indicates that there is a significant difference in the effect of two treatments under consideration. Significant difference in two treatments is denoted by upper bar (‾) over that pair. The two strategies which are without bar are mutually replaceable strategies. Depending on water savings, applicability and cost effectiveness, one can choose any one of these two strategies appropriately. Whereas, for those pair of strategies paired under bar, the strategy resulting in higher yield shall be opted.

3.11 Closure

Penman Monteith model is very useful to estimate daily potential evapotranspiration using daily climatological data. Further, dual crop coefficient approach of FAO-56 separately computes soil evaporation or surface moisture depletion and transpiration under normal and water stress condition. WEAP-MABIA model is useful tool to compute actual evapotranspiration and soil moisture balance as it uses Penman Monteith Method with dual crop coefficient approach. MABIA is an improvement over CROPWAT. The effective precipitation estimated by SCS method and taken as an input in soil moisture balance for calculating crop water requirements will be of great benefit. Water use efficiency and irrigation water use efficiency assists in evaluating the various strategies adopted for crop. Comparing the various strategies with some standard strategy in different scenarios gives a scope to make improvement in the selected strategy. Statistical tools provide a help in decision making for usage of a particular strategy. Description of study area and data collection is described in next chapter.