UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

CHAPTER 1

GENERAL INTRODUCTION

1.1 Botany and ecology of hot pepper

Hot pepper (*Capsicum* spp.), commonly known as chili, is the world's third most important vegetable after potatoes and tomatoes in terms of quantity of production. World production of chili and pepper is 28.4 million tons both dry and green fruit from 3.3 million ha, with an annual growth rate of 0.5% (FAO, 2007). Authorities generally agree that *Capsicum* originated in the new world tropics and subtropics (Mexico, Central America, and Andes of South America) over 2000 years ago (Walter, 1986). Chili belongs to the family *Solanaceae* and genus *Capsicum*. The genus *Capsicum* comprises 20-30 species (Lovelock, 1973). The species *annuum,* however, is the most commonly cultivated (Smith *et al*., 1998).

As a food, pepper has little energy value but it is an excellent source of vitamins A and C and a good source of vitamin B2, potassium, phosphorus, and calcium. The high nutritive value of pepper results in a high market demand year round. Pepper fruits are used in salads, pickles, stuffing, spices, sauce, and as a dried powder. The leaves are used in salads, soups, or eaten with rice (Lovelock, 1973).

Hot peppers are adapted to hot weather conditions. Day temperatures of 24 to 30 °C and night temperatures about 10 to 15 °C are ideal for growth. They are sensitive to freezing temperatures, while temperatures above 32 °C can reduce pollination, fruit set and yield (Smith *et al*., 1998). They are considered to be quantitative short day plants (Demers & Gosselin, 2002).

The crop is grown extensively under rainfed conditions and high yields are obtained with rainfalls of 600 to 1250 mm that are well distributed over the growing season (Doorenbos & Kassam, 1979; Smith *et al*., 1998). Hot pepper production in semi-arid and arid regions, however, depends on irrigation because of unreliability of rainfall, both in terms of quantity and distribution (Wein, 1998). The shallow root system (Dimitrov &

Ovtcharrov, 1995), high stomatal density, large transpiring leaf surface and the elevated stomata opening further make hot pepper plants susceptible to water stress and make irrigation an essential component in hot pepper production (Wein, 1998; Delfine *et al*., 2000). Furthermore, hot peppers, being a labour-intensive high value cash crop, necessitate the use of irrigation.

1.2 Irrigation, irrigation scheduling and deficit irrigation

A rise in the demand for agricultural products due to population growth in many parts of the world and the need to optimize productivity and overcome yield reduction or crop failure due to low and/or erratic rainfall distribution are the main reasons necessitating irrigation agriculture (Hillel & Vlek, 2005). At present approximately 80% of all the available fresh water supply in the world is used for agriculture and food production (Howell, 2001). In many countries where agriculture is the primary economic activity, agriculture accounts for over 95% of the water-use (UN-Water, 2007). However, the amount of water available for irrigation is consistently declining as a result of pressure from other competing demands (domestic, recreation and industrial uses).

Excess water application in irrigation is one of the main reasons for degradation of agricultural land. Huge areas of land become unusable for agriculture due to the rise of water tables and high concentrations of salts in the soil profile as a result of inappropriate irrigation (Ali *et al*., 2001; Smedema & Shiati, 2002; Hillel & Vlek, 2005). Rapid spread of diseases that infect human beings such as malaria (Jumba & Lindsay, 2001) and rift valley fever (Morse, 1995), as well as environmental degradation are the likely result of poorly planned and implemented irrigation projects. This calls for optimization of irrigation project planning and optimum use of the water available for irrigation. Generally, optimization of irrigation water management is necessary for structural (irrigation system design), economic (saving water and energy), and environmental reasons (salt accumulation in soil surface and agro-chemicals leaching into ground water) (Annandale *et al*., 1999).

Irrigation improves yield, not only by direct effect on mitigating water stress, but also by encouraging farmers to invest in inputs like fertilizers and improved cultivars, in which they are otherwise reluctant to invest due to uncertainty of crop production under rainfed conditions (Smith, 2000; Hillel & Vlek, 2005). Irrigation can also prolong the effective crop-growing period in areas with extended dry seasons, thus permitting multiple cropping per year where only a single crop would otherwise be possible (Hillel & Vlek, 2005).

Improved return from agricultural inputs and in environmental quality from irrigation can be achieved, among others, through practicing irrigation scheduling (Itier *et al*., 1996; Home *et al*., 2002) and deficit irrigation (English & Raja, 1996; Nautiyal *et al*., 2002; Zhang *et al*., 2002). Irrigation scheduling is a practice that enables an irrigator to use the right amount of water at the right time for plant production. Currently, several methods of irrigation scheduling are available. The different irrigation scheduling approaches employ soil, plant or atmosphere or the combination of two or three components of the soil-plant-atmosphere continuum (SPAC) as their basic framework. Examples of the soil-based approach are monitoring soil water by means of tensiometers (Cassel & Klute, 1986), electrical resistance and heat dissipation soil water sensors (Campbell & Gee, 1986; Jovanovic & Annandale, 1997), or neutron water meters (Gardner, 1986). Crop water requirements can also be determined by monitoring atmospheric conditions (Doorenbos & Pruitt, 1992). Pan evaporation, which incorporates the climatic factors that influence evapotranspiration into a single measurement, has been used to schedule irrigation for several crops (Elliades, 1988; Sezen *et al*., 2006).

Plant water status is also often used as an indicator of when to irrigate (Bordovsky *et al*., 1974; O'Toole *et al*., 1984). However, most physiological indices of plant water stress (leaf water potential, leaf water content, diffusion resistance, canopy temperature) involve measurements that are complex, time consuming and difficult to integrate, and are also subject to errors (Jones, 2004).

Alternatively, a system that integrates our understanding of the SPAC as mechanistically as possible can rather give the best estimates of plant water requirements. According to this concept, the soil water availability is not only governed by the soil water status, but also by plant and climate attributes (Hillel, 1990). Currently the use of this approach is expanding because of better understanding of the SPAC and the ready availability of computer facilities to compute huge amounts of data that would have been difficult to analyze by hand. To this end, various computer software programs are available that utilize soil, plant, atmosphere and/or management data to estimate plant water requirements (Smith, 1992; Crosby, 1996; Annandale *et al*., 1999; Crosby & Crosby, 1999; Rinaldi, 2001).

Annandale *et al*. (1999) showed, the Soil Water Balance (SWB) model could realistically predict plant water requirements for many field, vegetable and fruit crops. The SWB model is a mechanistic, user friendly, daily time step, and generic crop growth model. It is capable of simulating yield, different growth processes, stress days, field water balance components, etc. However, before one can use the SWB model, there is a need to determine crop-specific model parameters and calibrate the model, and evaluate it, using independent data sets to ensure the adaptability of the model to diverse crop species or cultivars and growing conditions if this has not already been done for the crop of interest. In the absence of such detailed and expensive crop-specific model parameters, an FAO crop factor approach can be utilized to calculate water requirements and schedule irrigation of crops (Allen *et al*., 1998).

Deficit irrigation, the deliberate and systematic under-irrigation of crops, is one of the water-saving strategies widely applied (English & Raja, 1996; Nautiyal *et al*., 2002; Zhang *et al*., 2002). It can increase water-use efficiency of a crop by reducing evapotranspiration whilst maintaining yield comparable to that of a fully irrigated crop. Deficit irrigation could help not only in reducing production costs, but also in conserving water and minimizing leaching of nutrients and pesticides into groundwater. However, before implementing such a strategy across all crops, there is a need to investigate the disadvantages and benefits of deficit irrigation, especially for water stress sensitive crops like *Capsicum* species. Other agronomic factors such as planting density and cultivar to be grown should also be considered to improve water-use efficiency.

Concomitantly, other cultural practices that enhance water-use efficiency needs to be considered. Correct cultivar selection, tillage, mulching, crop residue management, optimum plant spacing, proper fertilization and disease protection are among the cultural practices that are at our disposal to select the best combination of conditions to ensure maximum yield and thereby improve water-use efficiency (Wallace & Batchelor, 1997 as cited by Howell, 2001). Furthermore, collecting and analyzing long-term climatic data of a region helps to understand the evaporative demand of the atmosphere and the water supply and its distribution in a given growing season. This information, coupled with crop data can enable us to generate irrigation calendars using irrigation scheduling computer software.

An irrigation calendar is a simple chart or guideline that indicates when and how much to irrigate. It can be generated by software using data of long term climatic, soil, irrigation type and crop species, and management. It can be made flexible by including real-time soil water and rainfall measurements in the calculation of water requirements of a crop. Work by Hill & Allen (1996) in Pakistan and USA, and by Raes *et al.* (2000) in Tunisia have shown a semi-flexible irrigation calendar facilitated the adoption of irrigation scheduling due to minimum technical knowledge required in understanding and employing irrigation scheduling.

In this regard, the SWB model is equipped with the necessary functionality to generate irrigation calendars from climatic and crop data. Finally by adopting improved cultural practices, proper irrigation and improved use of precipitation, the water-use efficiency of hot pepper can be improved and environmental degradation due to over-irrigation can be reduced.

1.3 Justification of the study

Despite the fact that more than 80% of the world's fresh water resources are used for agriculture, a lack of water is still one of the most limiting environmental factors to crop production worldwide. This is partly because the population distribution and the amount of available fresh water distribution do not correspond (UN-Water, 2007). The intensity of the problem is felt more in arid and semi-arid regions of the world, where water is a scare resource than in other more humid areas.

Hot pepper is a warm season, high value cash crop. Generally, its production is confined to areas where available water is limited and, therefore, irrigation is standard practice in hot pepper production (Wein, 1998). A multitude of rainfall and irrigation management and cultural practices are available for the purpose of increasing water-use efficiency of crop production (Smith, 2000; Wallace & Batchelor, 1997 as cited by Howell, 2001; Passioura, 2006). Cultivar selection and optimum planting density are some of the cultural practices that can be exploited to increase the efficiency of water use.

The efficiency of water use could also be improved by adopting appropriate irrigation scheduling and the practice of deficit irrigation. Various methods of irrigation scheduling are available, but a system that combines the soil-plant-atmosphere continuum usually gives best estimates of the water requirements of plants (Jones, 2008). The SWB model is a computer program that is used to schedule irrigation and simulate crop growth (Annandale *et al*., 1999). To use this software, it is required that crop-specific model parameters be determined. The software also needs to be evaluated and calibrated before applying it to schedule irrigation for a particular crop under specific growing conditions. Where computer accessibility is a problem for irrigation scheduling and the know-how to use computers is lacking, the SWB model can be used to generate site-specific irrigation calendars, for a crop in a particular region based on long-term climatic data. Furthermore, as hot pepper is a very sensitive crop to water stress, a thorough investigation is imperative to ascertain the applicability of deficit irrigation in hot pepper production.

1.4 Objectives of the study

The study was conducted with the following objectives:

- to assess yield of hot pepper cultivars under varying irrigation regimes,
- to assess yield of hot pepper cultivars under different plant populations,
- to understand whether varying row spacing affects hot pepper response to different irrigation regimes,
- to understand whether cultivar differences affects hot pepper response to irrigation regimes,
- to evaluate growth and development of hot pepper under different irrigation regimes,
- to establish an FAO-type crop factor database for hot pepper cultivars
- to determine crop-specific model parameters under contrasting irrigation regimes

and plant populations,

- to calibrate and validate the SWB model for hot pepper cultivars,
- to determine the cardinal temperatures of hot pepper and to calculate the thermal time requirements for various developmental stages of hot pepper, and
- to determine the water requirements of one popular hot pepper cultivar from Ethiopia and generate irrigation calendars for hot pepper growing regions of Ethiopia.

CHAPTER 2

LITERATURE REVIEW

2.1 The role of water in plants

Water is one of the most common and most important substances on the earth's surface. It is essential for the existence of life, and the kinds and amounts of vegetation occurring in various parts of the earth's surface depend more on the quantity of water available than on any other single environmental variable (Kramer & Boyer, 1995).

Water constitutes 80-90% of the fresh mass of most herbaceous plant material and over 50% of the fresh mass of woody plants. Physiological activities of plants are closely related to the plant tissue water content (Kriedemann & Downton, 1981). Water is the solvent in which gasses, minerals, and other solutes enter plant cells and move from organ to organ. It is a reactant in many important biochemical processes, including photosynthesis and hydrolytic processes. Another role of water is in the maintenance of turgor, which is essential for cell enlargement and growth and for maintaining the form of herbaceous plants (Kramer & Boyer, 1995).

Water stress at physiological level causes loss of turgor, and resulting in setting of wilting. It also leads to cessation of cell enlargement, closure of stomata, reduction in photosynthesis, and interference with many other basic metabolic processes. Sub-lethal water stress usually results in the reduction of biomass production and economic yield in plants (McIntyre, 1987). The order in which physiological processes are serially affected by water stress seems to be growth, stomatal movement, transpiration, photosynthesis and translocation. Eventually, continued dehydration causes disorganization of the protoplasm and death of most organisms (Deng *et al*., 2000).

2.2 Water availability for crop production in semi-arid and arid regions

Arid and semi-arid regions comprise almost 40% of the world's land area (Parr *et al*., 1990; Gamo, 1999). Aridity is commonly expressed as a function of rainfall and temperature. A climatic aridity index, which is a ratio of precipitation to potential evapotranspiration, is a term coined to describe the degree of aridity. The evapotransipration is calculated following Penman procedure, which takes into account atmospheric humidity, solar radiation, temperature and wind. Arid zone has aridity index of 0.03 to 0.2 and semi-arid has 0.2 to 0.5 (FAO, 1989). A simple dictionary definition expresses aridity in terms of rainfall amount and vegetation types. According to Freedictionary (2008), semi-arid is defined as: "land that is characterized by relatively low annual rainfall of 250 mm to 500 mm and having scrubby vegetation with short, coarse, grasses and not completely arid." Arid is defined as: "land lacking water, especially having insufficient rainfall to support trees or woody plants."

Arid and semi-arid regions are characterized by unreliable rainfall, high radiation load and high evaporative demand, with soils generally of poor structural stability, low water holding capacity and low fertility (Parr *et al*., 1990; Monteith & Virmani, 1991). Farmers in this region are more concerned about disaster avoidance than yield maximization for the fact that crop risk is a given (Badini & Dioni, 2001).

Production and productivities in arid and semi-arid regions of the world are largely limited for lack of adequate water supply during the growing season. Traditionally irrigation has been practiced as the way to meet water shortage in crop production. As water is becoming a scarcer resource in these regions, there is a need to adopt irrigation and cultural practices that guarantee greater water-use efficiency.

2.3 Increasing water-use efficiency

Water availability is generally the most important natural factor limiting productivity and expansion of agriculture in arid and semi-arid regions of the world. To satisfy future food demands and growing competition for water, more efficient use of water in both rainfed and irrigated agriculture will be essential. Such measures would include rainfall conservation, reduction of irrigation water loss, and adoption of cultural practices that enhance water-use efficiency (Smith, 2000; Passioura, 2006).

2.3.1 Breeding crops for improved water-use efficiency

Genetic improvement in water-use efficiency (WUE) may lead to increased productivity under water-limited conditions. Genetic variability in WUE has been documented for many plant species and cultivars within a species (Turner *et al*., 2001; Condon *et al*., 2004). Physiologists have identified a wide range of morphological, physiological and biochemical traits that contribute to yield improvement of crops in drought-prone environments. Plant selection for shorter time to flowering has been successful for environments in which terminal drought is likely (Thomson *et al*., 1997; Siddique *et al*., 1999). In environments where the timing of drought is persistent or unpredictable, plants with high capacity of abscisic acid accumulation (Innes *et al*., 1984) and/or with high heat tolerance (Srinivasan *et al*., 1996) traits are reported to perform well as opposed to plants lacking such characteristics.

According to Fisher (1981) in water limited environments, yield (Y) is a function of the amount of water passing through transpiration (T), the efficiency with which transpiration water is utilized to produce dry matter (TE), and the partitioning of dry matter into the reproductive component (HI), such that:

$$Y = T \times TE \times HI \qquad (2.1)$$

Increasing the amount of water transpired (T) by a genotype can be achieved by two major strategies, which are under genetic control and can therefore be manipulated by breeding. The first involves increasing T relative to soil evaporation (E_s), while the other involves more efficient extraction of soil water, especially from deep in the soil profile (Turner *et al*., 2001).

In environments where evaporative demand is high and water supply is low, any strategy that increases canopy cover early in the life of the crop should increase the proportion of T relative to ET and thereby increase Y. Increased canopy cover can be achieved genetically as has been discussed by Rebetzke & Richards (1999), which would contribute to the reduction of E_s in relation to T.

The ability of roots to exploit water reserves in the subsoil strongly influences productivity of crops by the direct effect on increasing the amount of T and also indirectly by influencing the timing of supply (Passioura, 1977). A positive correlation between rooting depth and yield has been reported in peanut (Ketring, 1984) and in soybean (Cortes & Sinclair, 1986). This is attributed to the fact that increased root depth allows better water capture and increased T.

A number of research results indicated the presence of considerable genotypic variation in TE among cultivars (Hammer *et al*., 1997; Byrd & May II, 2000; Passioura, 2006; Ullah *et al*., 2008). Genotypic variations in TE can be assessed with accurate estimates of both T and top dry matter (TDM) and this trait can be utilized as a selection criterion. However, in the glasshouse the procedure is extremely time consuming and tedious and in the field it requires elaborate minilysimeter facilities for accurate measurement of T and TDM, after accounting for E_s and root biomass (Turner *et al*, 2001). Work in peanut by Nageswara Roa & Wright (1994) demonstrated the possibility of using correlated traits like specific leaf area as surrogate measure of TE. Leaf ash content and its elements have also been shown to be significantly correlated with TE in a number of species (Mayland *et al*., 1993).

The last variable of the equation that relates to yield and yield components, which is amenable to genetic manipulation for increasing water-use efficiency, is harvest index. This simple ratio varies on the ability of a genotype to partition current assimilates and the reallocation of stored or structural assimilates to the seed and/or fruit. Yield stability in terminal drought environments has been attributed to crops' ability to redistribute assimilates accumulated prior to flowering and immediately post-flowering to the seed during the postflowering period (Turner *et al*., 2001). Genotypic variation in the extent of partitioning and reallocation of assimilates to the seed have been reported in soybean (Westgate *et al*., 1989), in peanut (Wright *et al*., 1991) and in chickpea (Singh, 1991) under water deficit growing conditions.

Thus, by genetically improving one or more variables of the equation that describes the relationship between yield and yield components, water-use efficiency could be improved in water limited environments.

2.3.2 Water-saving agriculture

Water-saving agriculture refers a comprehensive exercise using every possible water-saving measure in whole-farm production, including the full use of natural precipitation as well as the efficient management of an irrigation network (Wang *et al*., 2002; Deng *et al*., 2006). The following are the major strategies to achieve water-saving agriculture.

2.3.2.1 Increasing precipitation use efficiency

Rainfed agriculture remains the dominant crop and forage production system throughout the world, and hence the improvement of food and fibre production requires that we increase precipitation use efficiency (Smith, 2000; Hatfield *et al*., 2001). Furthermore, rainfed agriculture is characterized by seasonal variation in rainfall distribution and amount, which calls for improvement in precipitation use efficiency (Smith, 2000). Precipitation use efficiency is a measure of the biomass or grain yield produced per increment of precipitation (Hatfield *et al*., 2001). Various practices are employed to improve precipitation use efficiency, among which timely planting, minimum tillage, new cultivars, mulching and soil nutrient management are the principal ones (Turner, 2004).

The term water harvesting is defined as the collection of surface runoff and its use for irrigated crop production under dry and arid conditions. In some cases special measures are taken to increase the runoff to water harvesting areas. These measures generally improve precipitation use efficiency as they allow holding back, collecting, and hence rendering useful the fast running-off fraction of precipitation water that otherwise would have been lost (Wolff & Stein, 1999).

The effect of tillage on the soil water profile, infiltration, soil evaporation and runoff varies depending on the type of tillage and mulch management. Burns *et al*. (1971) showed that tillage disturbance of the soil surface increased soil water evaporation compared with untilled areas. Cresswell *et al*. (1993) observed that tillage of bare soils increased saturated hydraulic conductivity, while excessive tillage caused the lowest conductivities because of the increase in air-filled pores. In contrast to Cresswell *et al.* (1993), Christensen *et al.* (1994) found that more soil water was conserved during fallow periods with no tillage than clean till. Pikul & Aase (1995) stated that no tillage has advantage over tillage because surface cover is maintained, and this reduces the potential for soil crusting and erosion. Furthermore, they found that decreasing tillage showed a trend towards improving WUE because of improved soil water availability through reduced evaporation losses.

Crop residue and mulches are known to reduce soil water evaporation by reducing soil temperature, impeding vapour diffusion, absorbing water vapour onto mulch tissue, and reducing the wind speed gradient at the soil-atmosphere interface (Hatfield *et al*., 2001). Azooz & Arshad (1998) found higher soil water contents under no tillage as compared with moldboard plough in British Columbia. Johnson *et al*. (1984) reported that more water was available in the upper 1 m under no-tillage compared with other tillage practices in Wisconsin. This increase was attributed to the fact that the crop residue provided a barrier to soil water evaporation and the absence of tillage operations limited the extent of soil disturbance. A study conducted in Jordan by Abu-Awwad (1999) on onion revealed that covering the soil surface significantly increased transpiration compared with an open soil surface treatment, because of the elimination of wet soil surface evaporation, which increased the water available for transpiration. He reported that covering the soil surface reduced the amount of irrigation water required by an onion crop by about 70% for all irrigation treatments as compared with the amount of irrigation water required by the bare soil surface treatment.

2.3.2.2 Increasing irrigation use efficiency

This refers to the use of irrigated farming practices with the most economical exploitation of the water resources. Irrigation management that enables reduced water supply to the crop, while still achieving a high yield forms the pillar of the system. Irrigation management that also minimizes leakage and evaporation from storage facilities and in transport contributes positively towards efficient exploitation of water resources.

Irrigation scheduling

Water-use efficiency can be improved through practicing irrigation scheduling (Itier *et al*., 1996; Howell, 2001; Home *et al*., 2002). Irrigation scheduling is the practice of applying the right amount of water at the right time for crop production. Irrigation scheduling is conventionally based on soil water measurement, where the soil water status is measured directly to determine the need for irrigation. Examples are the monitoring of soil water by means of tensiometers (Cassel & Klute, 1986), electrical resistance and heat dissipation soil water sensors (Campbell & Gee, 1986), or neutron water meters (Gardner, 1986). A potential problem with soil water based approaches is that many features of the plant's physiology respond directly to changes in water status in the plant tissues, rather than to changes in the bulk soil water content. The actual tissue water potential at any time, therefore, depends both on the soil water status and on the rate of water flow through the plant and the corresponding hydraulic flow resistance between the bulk soil and the appropriate plant tissues. The plant response to a given amount of soil water, therefore, varies as a complex function of evaporative demand. Other disadvantages of using soil water measurement for irrigation scheduling include soil heterogeneity. This requires many sensors and selecting positions that are representative of the root zone is difficult (Jones, 2004).

The second approach is the use of plant stress sensing apparatus, where irrigation scheduling decisions are based on plant responses rather than on direct measurements of soil water status (Bordovsky *et al*., 1974; O'Toole *et al*., 1984). Examples are visual observation of the plant leaf, leaf water potential, stomata resistance, canopy temperature, cell enlargement, relative leaf water content, plant organ diameter, photosynthesis rate, abscisic acid hormone levels, leaf osmotic potential, and sap flow. However, due to a multitude of shortcomings related to this approach, the feasibility thereof, especially on large scale, becomes questionable. The majority of the system requires instruments beyond the reach of ordinary farmers, as well as complex technical know-how. Time required to use these instruments also discourages their ready application. On top of this, if our measurement target is on one aspect (plant) of the soil-plant-atmosphere continuum, it will be difficult to estimate realistically the plant water requirement. This is because the plant system involves many complex and intricate processes (Jones, 2004).

The third option is calculation of the soil water balance components, where the soil water status is estimated by calculating the change in soil water over a period. This is given by the difference between the inputs (irrigation plus precipitation) and losses (runoff plus drainage plus evapotranspiration). The input parameters are easy to measure, using conventional instruments like rain gauges for rainfall and irrigation, and water meters for irrigation. Runoff and drainage could either be estimated from soil physical properties or directly measured *in situ* or could be assumed negligible based on soil conditions and water supply. Evapotranspiration can be estimated by monitoring atmospheric conditions (Doorenbos & Pruitt, 1992; Allen *et al*., 1998). Pan evaporation, which incorporates the climatic factors influencing evapotranspiration into a single measurement, has often been used to estimate evapotranspiration of several crops (Elliades, 1988; Sezen *et al*., 2006).

Currently the use of the soil water balance approach is on the increase because of better understanding of the soil-plant-atmosphere continuum and the availability of computer facilities to compute complex equations. Various computer software programs are available that utilize soil, plant, atmosphere and management data to estimate plant water requirements. Annandale *et al*. (1999) showed, on many fruit, vegetable and field crops, the Soil Water Balance (SWB) model to realistically predict plant water requirements. The SWB model is a mechanistic, user friendly, daily time step, and generic crop growth model. It is capable of simulating yield, different physiological processes, stress days, and field water balance components. Elsewhere, different authors (Smith, 1992; Crosby & Crosby, 1999; Rinaldi, 2001) employing similar principles and working on different crops under different conditions showed the practicality of using computer software in irrigation scheduling. Furthermore, collecting and analyzing the long-term climatic data can help to understand typical evaporative demand of the atmosphere and the water requirements in a growing season for better water management (Smith, 2000). This information, coupled with crop data, can enable the generation of irrigation calendars, using computer software.

An irrigation calendar is a simple chart or guideline that indicates when and how much to irrigate. It can be made flexible by including real-time soil water and rainfall measurements in the calculation of water requirements of a crop. Work by Hill & Allen (1996) in Pakistan and USA, and by Raes *et al.* (2000) in Tunisia have shown a semi-flexible irrigation calendar facilitated the adoption of irrigation scheduling due to less technical knowledge required in understanding and employing the irrigation scheduling.

In this regard, the SWB model is equipped with the necessary capability to enable the development of irrigation calendars and estimation of water requirements of plants from climatic, soil, crop and management data (Annandale *et al*., 1999, Geremew, 2008).

Deficit irrigation

Deficit irrigation, the deliberate and systematic under-irrigation of crops, is a common practice in many areas of the world (English & Raja, 1996; Nautiyal *et al*., 2002; Zhang *et al*., 2002). Fereres & Soriano (2007) defined deficit irrigation as the application of water below the evapotranspiration (ET) requirements. Therefore, irrigation supply under deficit irrigation is reduced relative to that needed to meet maximum ET. Government agencies in water deficit countries such as India and South Africa have endorsed the concept of deficit irrigation by recommending that irrigation planning be based on '50% dependable' supply of water (Chitale, 1987). Thus, the main driving reason for adoption of deficit irrigation is limited and reliable availability of the water supply.

The economic and ecological advantage that could be derived from deficit irrigation is multifaceted. In economic terms, the potential benefits of deficit irrigation derive from three factors: increased irrigation efficiency, reduced costs of irrigation and the opportunity cost of water (English *et al*., 1990; English & Rajan, 1996). Ecological benefits of deficit irrigation include preventing rising water tables in areas where the water level is near the soil surface. Deficit irrigation can also help in minimizing leaching of agrochemicals to groundwater (Home *et al*., 2002).

Deficit irrigation has various features depending on how, when, where and why it is administered (Fereres & Soriano, 2007). In the humid and sub-humid zones, irrigation has been used to supplement rainfall as a tactical measure during drought spells to stabilize production. This type of irrigation is called supplemental irrigation (Debaeke & Abourdrare, 2004), and the goal is to maximize yield and eliminate yield fluctuations caused by water deficit. Similarly, in arid zones, small amounts of irrigation water are applied to winter crops that are normally grown under rainfed conditions (Oweis *et al*., 1998). Another form of deficit irrigation is called sustained deficit irrigation or limited irrigation (Wang *et al*., 2002) where irrigation water is applied below ET continuously throughout the growing season. The theoretical basis for this type of irrigation includes crop-water relation, impacts of the water deficit on crop growth at different stages, and the physiological drought resistance of crops (Wang *et al*., 2002).

Another variant of deficit irrigation is called regulated deficit irrigation (RDI). The theoretical basis of RDI is crop physiology and biochemistry. RDI is conducted on crops according to their characteristics and water requirements. In this type of deficit irrigation, certain water stresses are imposed at the beginning of some crop growth stages which can change intrinsic plant physiological and biochemical processes, regulate the distribution of photosynthetic products to different tissue organs, and control the growth dynamics between the aerial parts and the roots to improve reproductive growth and to eventually increase crop yield (Wang *et al*., 2002).

A deficit irrigation form recently developed, called controlled alternative irrigation or partial root zone drying (PRD) is an irrigation system where alternate sides of the root system are irrigated during alternate periods (Wang *et al*., 2002; Chaves & Oliveira, 2004). In PRD the maintenance of the plant water status is ensured by the wet part of the root system, whereas the decrease in water-use derives from the closure of stomata promoted by dehydrating roots. The principle of this deficit irrigation is that crop roots can produce signals during water stress, and the signals can be transmitted to leaf stomata to control their apertures at optimum levels.

Another example of deficit irrigation is where irrigation is planned in such a way that "room for rain" is left. In this method, irrigation is applied to refill part of the depletion field capacity, while the remaining portion of the soil water depletion is expected to be refilled by rain (Jovanovic *et al*., 2004). The deficit level imposed in this system depends on the level of sensitivity of a crop grown to water deficit and the rainfall distribution of an area.

Deficit irrigation has been successful in most cases in tree crops for a number of reasons. First, economic return in tree crops is often associated with factors such as crop quality, and second the yield determining processes in many fruit trees are not sensitive to water deprivation at some developmental stages (Johnson & Handley, 2000). Experiments with deficit irrigation have been successful in many fruit and nut tree species such as almond (Goldhamer & Viveros, 2000), citrus (Domingo *et al*., 1996), apple (Mpelasoka *et al*., 2001), mango (Spreer *et al*., 2007) and wine grapes (Bravdo & Naor, 1996; MacCarthy *et al*., 2002; Fereres & Evans, 2006), almost always with positive results.

Conflicting results were reported on the effects of deficit irrigation on annual crops, probably depending upon the type and intensity of deficit irrigation and crop species considered. A study conducted by Zhang *et al*. (2002) on winter wheat on the North China Plain revealed water-savings of 25-75 % by applying deficit irrigation at various growth stages, without significant yield loss. Similar results have been reported for groundnuts in India (Nautiyal *et al*., 2002). In hot pepper, Dorji *et al*. (2005) observed a 21% increment in total soluble solids and better colour development with deficit irrigation as compared to partial rootzone drying and full irrigation. However, Shock & Feibert (2002) reported a reduction in potato tuber yield of as much as 17% due to deficit irrigation. They further reported a significant reduction in both external and internal tuber quality because of deficit irrigation.

Besides yield and quality reduction due to deficit irrigation in some crop species, the other consequence of deficit irrigation is the greater risk of increased soil salinity due to reduced leaching, and its impact on the sustainability of irrigation (Fereres & Soriano, 2007). Whenever irrigation is applied, salts are transported from a water source to a root zone (soil surface) and the salts accumulate there as evapotransipration usually removes the water, leaving the precipitated salts. This salinization becomes serious in arid and semi-arid areas where water is scarce (Smedema & Shiati, 2002). This is because the rainfall in these areas is not adequate to provide the leaching requirement to remove excess salts accumulated periodically. Deficit irrigation if taken as an option to overcome scarcity of water in these areas, salinization could become a problem, as it does not provide the extra water that is required to leach the accumulated salts in the soil surface. Thus, adoption of deficit irrigation without precautionary measures to periodically perform leaching of concentrated salts poses a problem for sustainability of irrigation.

2.4 A brief description of the Soil Water Balance model

The Soil Water Balance (SWB) model is a multi-soil layer, daily time step, generic crop, mechanistic, user-friendly, irrigation scheduling model (Annandale *et al*., 1999). It simulates the soil water balance and crop growth using crop-specific model parameters. It is based on the improved version of the soil water balance model described by Campbell & Diaz (1988). The SWB model contains three units, namely the weather unit, soil unit and crop unit. The weather unit of SWB calculates Penman-Monteith grass reference daily evapotranspiration (ETo) as a function of daily average temperature, vapour pressure deficit, radiation and wind speed, according to the recommendations of the Food and Agriculture Organization of the United Nations (Allen *et al*., 1998). The soil unit simulates the dynamics of soil water movement in the soil profile in order to quantify transpiration and evaporation. In the crop unit, the SWB model calculates crop dry matter accumulation in direct proportion to the vapour pressure deficit-corrected dry matter/water ratio (Tanner & Sinclair, 1983). The crop unit also calculates radiation-limited growth (Monteith, 1977) and takes the lesser of the two. This dry matter is partitioned to the roots, stems, leaves and grains or fruits. Partitioning depends on phenology, calculated with thermal time and modified by water stress.

Site specific input data to run the model includes daily weather data, altitude, latitude, and hemisphere. In the absence of measured data on total solar radiation, average wind speed, and average vapour pressure; the model is equipped with functions for estimating these parameters from available weather data according to the FAO 56 recommendation (Allen *et al*., 1998).

Soil input data such as the runoff curve number, drainage fraction and maximum drainage rate, soil layer characteristics (thickness, volumetric soil water content at field capacity and permanent wilting point, initial volumetric water content, and bulk density) are also required to run the model.

Since SWB is a generic crop growth model, model parameters specific for each crop have to be determined. The following are the crop-specific model parameters that are required to run the growth model of SWB: canopy extinction coefficient for total solar radiation (Ks), vapour pressure deficit-corrected dry matter/water ratio (DWR), radiation use efficiency (E_c), base temperature (T_b), optimum temperature for crop growth (T_m), cut-off temperature (T_x), maximum crop height (Hc_{max}), day degrees at the end of vegetative growth, day degrees for maturity, transition period day degrees, day degrees for leaf senescence, maximum root depth (RD_{max}), fraction of total dry matter translocated to heads, canopy water storage, leaf water potential at maximum transpiration (ψ_{lm}), maximum transpiration rate (T_{max}), specific leaf area (SLA), leaf-stem partitioning parameter (p), total dry matter at emergence, fraction of total dry matter partitioned to roots, root growth rate and stress index (Annandale *et al*., 1999).

2.5 Water requirements of peppers and water stress effects on peppers crops

The water requirements of peppers vary between 600 and 1250 mm per season, depending on regional climate and cultivar (Doorenbos & Kassam, 1979). The wide variation in water requirements of pepper is attributed to the broad genetic variation within the species and the wide range of environments the crop is adapted to.

The hot pepper plant (*Capsicum annuum* L.) has a shallow root system, which extracts 70 to 80 % of its water from the top 0.3 m soil layer (Dimitrov & Dvtcharrom, 1995). This, together with high stomatal density, a large transpiring leaf surface and an elevated stomatal opening, predispose the pepper crop to be vulnerable to water stress (Delfine *et al*., 2000).

Like other crops, optimum supply of water throughout the growing season is essential for optimum production of hot peppers. Water supply that is below or above optimum levels leads to deterioration in both quantity and quality of the pepper yield.

Mild water stresses in plants usually directly affect growth (cell elongation), whereas photosynthesis and translocation are less sensitive to water stress (Kramer & Boyer, 1995). The biochemistry of photosynthesis (namely, Rubisco characteristics) was not affected in sweet pepper by mild water stress; rather the observed reduction in photosynthesis was caused by limitation of carbon dioxide (CO_2) conductance due to partial closure of stomata (Delfine *et al*., 2000) as stomata serve for both CO_2 conduction and transpiration.

Pepper plants are most sensitive to water stress during flowering and fruit development (Katerji *et al*., 1993). According to Costa & Gaianquito (2002), the increased fruit dry yields due to the effect of increased water supply or irrigation was mainly attributed to a significant increment in fruit number. Improvement of average diameters and lengths of fruits, and pericarp thickness were also observed as more water was applied (Costa & Gaianquito, 2002). The reduction in fruit number due to water stress was attributed to flower abortion (Dorji *et al*., 2005), which results in a reduction of fruit number. Dorji *et al*. (2005), however, reported no significant differences in dry mass distribution among plant organs due to irrigation treatments. Stressing the pepper plant at the beginning of fruit set resulted in lower fruit number per plant and a high proportion of undersized fruits. Furthermore, the percentage of non-marketable fruits showed a significant share of blossom-end rot when plants are stressed at the beginning of fruit set or if continuously exposed to acute water stress throughout the growing season (Costa & Gaianquito, 2002).

Water stress not only affects production of a crop but also selected quality traits of the produce. The following are the most important horticultural quality attributes that are affected by water stress in hot peppers: total soluble solids, colour development, blossom end-rot symptoms, pericarp thickness, fruit diameter, fruit length, and nutritional value of fruits. Costa & Gaianquito (2002) observed a high proportion of discarded fruits due to blossom end-rot symptom in dry treatment and undersized fruits in wet treatment. The high proportion of undersized fruits in wet treatment was attributed to the high rate of fruit set in the treatment, compared to the dry one.

Conflicting results have been reported regarding the practicality of deficit irrigation for water conservation in hot pepper. Kang *et al*. (2001) and Dorji *et al*. (2005) suggest the use of deficit irrigation in hot pepper. However, others confirmed the sensitivity of pepper to water stress and the beneficial effects of abundant irrigation. Costa & Gianquinto (2002) and Beese *et al*. (1982) observed significant yield increases with water levels above 100 % evapotranspiration, indicating yield increases with additional water beyond the well-watered control. The inconsistency of the results reported may be attributed to differences in the cultivars used (Ismail & Davies, 1997; Jaimez *et al*., 1999) and in the growing conditions (Pellitero *et al*., 1993).

2.6 Planting density effect on growth, yield and water-use of plants

In modern crop production, crops are planted in a wide range of inter- and intra-row spacings giving different plant arrangements and plant population densities. The choice of a particular plant arrangement and plant population is dictated by crop species (cultivars), inputs used, irrigation system employed, machinery used for cultural practices, the method of harvesting employed, the end use of the produce, etc. It is usually a matter of compromise between convenience and productivity.

Knowledge of crop response to population density is useful for management decisions and it provides the basis for assessing the effects of intra-species competition (Jolliffe, 1988). Crops (cultivars) with vigorous growth habit are usually planted at a wider row spacing to avoid competition among neighbouring plants and also to prevent mutual shading in plant canopies. Disease prevalence and severity are also important considerations for a wider row planting option (Castilla & Fereres, 1990).

Plant population primarily affects the amount of radiation intercepted per plant (Villalobos *et al*., 1994). Light quality as modified by different plant populations may also play an important role on early plant growth and partitioning responses (Ballare *et al*., 1987). The yield advantage due to narrow spacing is usually attributed to the development of a full canopy in early development stages (Fukai *et al*., 1990). These full canopies, in turn, intercept more radiation and have a greater photosynthetic production than the partial canopy development that is usually observed in wider row spacings.

Plant densities beyond certain thresholds can adversely affect fruit quality and encourage disease development in pepper plants. Inadequate fruit colour development was also observed in over densely planted hot pepper (Stoffella & Bryan, 1988). This may be due to the inability of some of the fruit to be in direct sunlight, which is important for the development of carotenoid pigments. Poor ventilation is responsible for high disease incidence associated with high planting density in tomato, especially under greenhouse conditions (Castilla & Fereres, 1990).

Plant efficiency was suggested to increase with increasing plant population for bell pepper (Stoffella & Bryan, 1988; Lorezo & Catilla, 1995) and pepperoncini (Motsenbocker, 1996). Lorezo & Catilla (1995) reported a significantly higher yield due to high density planting. This higher yield is attributed to increased leaf area index (LAI), which in turn improved radiation interception (Lorezo & Catilla, 1995). Higher values of LAI in high density treatments led to an improved radiation interception and subsequently, to higher biomass and yield than in the low density treatment. Jolliffe & Gaye (1995) reported that as much as 47% variation in total fruit dry yield of pepper can be attributed to population density effects at 103 days after transplanting. At the end of the growing season, plant population density treatments accounted for 35% of the variation in the final cumulative fruit dry mass. Similarly, high density populations have been reported desirable for maximum yields in cayenne (Decoteau & Graham, 1994) and bell pepper (Russo, 1991; Locascio & Stall, 1994).

Plant spacing can also influence morphological development of peppers. Pepper and other plants grown in denser populations tend to be taller (Karlen *et al*., 1987; Stoffella & Bryan, 1988) and may set fruit higher on the plant than those grown in less-dense plantings. Narrow row spacing (higher population density) resulted in plants that were smaller (less leaf and plant mass), more upright, and produced less fruit yield per plant but higher fruit yield (tons ha^{-1}) and number ha^{-1}. This suggests that the high yield with narrow row spacing is attributed to higher plant population and fruit production per area, rather than higher pepper yield per plant or fruit size. Similar results were reported for cayenne pepper (Decoteau & Graham, 1994), bell pepper (Stoffella & Bryan, 1988) and Tabasco pepper (Sundstorm *et al*., 1984). Further benefit of narrow spacing are increased ease of harvesting in closely spaced plant due to plant's upright position with lower leaf area, which make locating fruits for hand removal easier (Motsenbocker, 1996).

Growing conditions and genotypes influence the relationship between planting density and crop yield (Taylor, 1980; Johnson *et al*., 1982; Tan *et al*., 1983). High yields as a result of high plant population are achieved under optimal water supply condition (Cantliffe & Phatak, 1975; O'Sullivan, 1980; Taylor, 1980; Taylor *et al*., 1982; Tan *et al*., 1983; Gan *et al*., 2002). Tan *et al*. (1983) reported similar cucumber yield for high and low plant populations when grown without irrigation, but they observed a significant plant population effects under irrigated conditions. Taylor (1980), working on soybean, observed no difference in yield among 0.25-, 0.5-, 0.75- and 1-m wide row spacings in a sub normal rainfall year, whereas, although not significant, yield tended to increase as row spacing decreased in normal rainfall seasons. For a growing season with rainfall above normal, soybeans in 0.25 m row spacing out-yielded those in 1.0 m rows by 17%.

The growing length dictates plant response to plant population (Villalobos *et al*., 1994). Accordingly, high potential sunflower yields under non-limiting conditions can be achieved by using short-cycle cultivars if plant population is high enough, whereas to exploit the yield potential of long-cycle sunflower, improvement in harvest index rather than plant population deserves attention. This is explained by the fact that in short-cycle cultivars optimum biomass per unit area is achieved as the density of planting is increased. In case of the long-cycle cultivars, within acceptable ranges of plant populations, optimum biomass per unit area tends to remain unchanged over longer growing seasons.