CHAPTER 1

GENERAL INTRODUCTION

The potential irrigable land in Ethiopia is estimated at about 3.5 million hectares, of which about 180 000 to 400 000 hectares have the potential to be developed as small-scale irrigation schemes (Tillman, 1981). This figure could change as more reliable data emerge from more detailed studies. To date, less than 200 000 ha has been developed and yet more land has to come under irrigation to feed the fast growing population, provide raw materials for local industries and combat the effect of recurrent droughts. Ethiopia is known to have abundant water resources that can be used for irrigated agriculture (MWRC, 1999). There are nine major rivers, most of them flowing to neighbouring countries, and a number of lakes with good quality irrigation water. The country's total surface water availability is estimated at about 110 billion m^3 (WRDA, 1990). On the other hand, the nine major river systems have an estimated total annual discharge of 102 billion m^3 (WRDA, 1990). Despite this potential land and water resources for irrigation, the country has long been known to have periodic food deficiencies (Ndege, 1996). Table 1.1 indicates the irrigation potential of the country in comparison to the current developed land area.

Recurrent droughts have been one of the major problems in Ethiopia during the past three decades. The occurrence of drought in most parts of the country is caused by either insufficient or no rainfall to support the seasonal water requirements of the rain-fed crop production and this gap is to be filled by supplementary irrigation. About 80% of the Ethiopian population is dependent on rain-fed agriculture and inadequate seasonal rainfall can cause serious food shortages that can adversely de-stabilise the social and economic life of the people (CIDA, 1997).

Table 1.1 Irrigation potential and the area of land already developed in different river basins of Ethiopia (WRDA, 1990).

No	Basins	Potential irrigable land (ha)	Actual irrigated area (ha)	Actual land developed (%)
1	Blue Nile	977 915	21 010	2.10
2	Awash	207 400	69 900	34.00
3	Rift Valley Lakes	112 300	12 270	10.00
4	Omo Ghibe	450 120	27 310	6.10
5	Genale Dawa	435 300	80	0.02
6	Wabi Shebele	204 000	20 290	9.90
7	Baro Akobo	748 500	350	0.05
8	Tekeze	312 700	1 800	0.57
9	Mereb	37 560	8 000	21.30
	Total	3 495 795	161 010	4.07

In Ethiopia, it is well known that even in relatively good rainfall years, there can be pockets of land that do not get sufficient precipitation to see a crop through to full production (IFAD, 2005).

A critical review of the drought in the country shows different alternatives for mitigating the problem. One of the alternatives is to improve the potential of traditional irrigation schemes for enhanced productivity as a strategic intervention to resolve food insecurity in the country (World Bank, 1999). A number of factors led to choosing the improvement of traditional irrigation schemes, of which the most prominent one was that irrigation increased the potential for producing more food

more consistently in the drought-prone food-insecure areas. During the raging drought in east Africa in the 1980s, irrigation has served as a means of rescue to several lives.

The improvement of small-scale and traditional irrigation comprises two major areas. The agronomic aspect of irrigation is one of the areas that requires a marked improvement, namely when to irrigate and how much water to apply. The other major activity, relevant to this issue, is the development of water-efficient and high-yielding crop varieties and the provision of these varieties and other crop management technologies to the farmer (MWRC, 1999).

In Ethiopia, traditional water diversions for irrigation were said to date far back. However, there is no recorded history that indicates where, when and how these traditional irrigation cultures were started and developed. At present, small-scale and traditional irrigation comprise about 40% of the total irrigated land in Ethiopia (Guijt & Thompson, 1994). Despite this, traditional water diversion, conveyance to farms, distribution and on-farm applications have not been improved and lead to a very low overall irrigation efficiency. Even though the management of traditional irrigation schemes were said to be more sustainable and environment-friendly in this country, there was no recorded information on which aspect of the management was sound, or on economic feasibility (Geremew, 1994; Geremew & Fentaw, 1994). The only known fact is that not much environmental degradation was observed under traditional irrigation practices compared to those of commercial schemes. The Natural Resources Management Department of the Ministry of Agriculture has tried to estimate the area of traditional irrigation that was only accessible by four-wheel drive vehicle (IFAD, 2005). In this brief estimation, irrigated lands that were less than a

hectare were not included, because there were either too many of them or they were inaccessible. On the other hand, even for the inventoried irrigated land, there was no recorded information on the methods of irrigation used, the amount of water applied or the watering intervals. Personal communications revealed that furrow irrigation methods were commonly used for annual crops and a combination of basin and border methods for perennial crops. In all cases, estimates of the water applied to different crops at various growth stages were not known at all. Neither the water user nor the extension agent had tried to introduce the concept of irrigation water measurement. Personal observations indicated that there could be over-irrigation in the upper lands and under-irrigation in the lower parts of the scheme due to shortages of water because of overall low irrigation efficiency. There also seemed to be no watering variation among various crops with reference to both amount and interval.

Traditional irrigation schemes are not at all supported by improved water management practices. Not only irrigation technologies, but also improved crop varieties, appropriate plant nutrient management, effective crop protection methods, farm mechanisation and market accessibilities are not in favour of traditional irrigation schemes. The Soil and Water Management Research Division at the Melka Werer Research Centre, the only centre conducting research on water management, has tried to produce appropriate water management technologies for commercial farms. They have identified irrigation methods, irrigation intervals and amounts in the Awash Valley for major crops, including cotton, groundnut, sesame, maize, wheat and a few horticultural and forage crops. The Awash Basin is an area developed by the state to produce commercial crops under state holding. This scheme operates under full-time irrigation, with mostly continuous mono-cropping to cotton. Water

management in the valley is performed by the State company, including the operation and maintenance of the system. Currently, only a few private producers are involved in the water management after secondary canals. Generally, it is unfortunate that the water management experience in this valley of more than 30 years could not be extrapolated to any part of the country out of that area. Even within the valley, salinities and sodicities are already developing, which require specialised management, depending on the nature and extent of the problem. Melka Werer Research Centre was advised by several consultants to concentrate on production of research technologies that can be used by farmers, rather than mechanised large-scale farms. Despite this, the Soil and Water Research Division of the Melka Werer Centre could not build enough manpower and facilities to cover the vast farmer-managed area.

It was deemed essential to monitor, evaluate and improve the water management practices of traditional irrigation schemes in Ethiopia. Before attempting to improve traditional irrigation, the actual constraints that require improvement needed to be identified. In addition, a brief insight into the current social structure was also important, since it has a significant effect on the performance of irrigation in the scheme. Hence, the following experiments were performed to achieve the desired goal of improved water management on traditional schemes.

1. A survey was conducted in Godino, a representative traditional irrigation scheme. This survey enabled the researcher to monitor and evaluate the current water management practices of the farmer, the irrigation method followed, irrigation intervals and application depth, and the form of existing

institutional structure of water management in the scheme. Two traditional practices were identified (Chapter 3);

2. Two traditional practices obtained from the survey were compared with two more scientific irrigation schedules to evaluate their performance. The result indicated that traditional methods performed poorly, which suggested that it be replaced by an efficient, simple and affordable method, namely the Soil Water Balance (SWB) model schedule (Chapter 4);
3. The suggested SWB scheduling method required determination of crop specific parameters in order to develop calendars. Therefore, four potato cultivars (one of the major crops in the scheme) were used and crop specific parameters were determined in order to develop future irrigation calendars (Chapter 5);
4. The processing quality of the four cultivars was evaluated as potatoes are mostly used for chipping (Chapter 6);
5. Since the SWB model provides deficit irrigation strategy and one major constraint recorded in the Godino scheme was the unavailability of irrigation water supply, crop-specific parameters were determined from the field experiment conducted on onions' critical growth stages to water stress. Onions are another important crop in the scheme (Chapter 7);
6. The SWB model simulations were calibrated and validated with the crop specific parameters generated from the three field experiments to evaluate model performance (Chapter 8); and
7. SWB irrigation calendars were developed, using the generated crop specific parameters for five different locations in Ethiopia, which could serve as a guideline for the extension services (Chapter 9).

A general discussion and recommendations follow in Chapter 10. Finally, results of this study indicate possible areas of improvement in developing a sustainable irrigation water management system for the traditionally irrigated schemes of Ethiopia.

CHAPTER 2

LITERATURE REVIEW

2.1 Community-based irrigation water management: the need for improved social structure

In the regions where agriculture has evolved from dry land farming to small-scale irrigation development, changes have occurred in the society, particularly in the economy and culture, where it led to the development of large and complex irrigation systems. One of the historical relationships between society and irrigation was reported to be situated along the southern edge of Mesopotamia at the foot of the Zagros Mountains and on the shores of the Persian Gulf (Thorne & Peterson, 1950). During this era, farmers and pastoralist communities of the Sahara, Arabia and Persia were forced to flee the droughts starting to occur in these vast areas, to take refuge in low alluvial valleys of the Indus, Euphrates, Tigres and Nile. Hailing from various backgrounds, these people, who were used to let their herds graze in these valleys, started to cultivate the edges and gradually made the necessary developments to ensure water delivery and draining of excess water (Thorne & Peterson, 1950). However, it took many centuries to set up the social organisations capable of building and maintaining these hydraulic developments and to ensure water management (David *et al*., 1998). Settlements of such types later on developed into villages and major cities that were surrounded by intensively farmed gardens and orchards (David *et al*., 1998).

Irrigation in many countries has been implemented to fulfil a combination of social and economic goals. In the process of enhancing the economic opportunities of rural populations, other problems are being alleviated in most communities of the world.

These include the slowdown of the farmer's migration from unrewarding farmlands to overcrowded urban areas as a result of providing increased supplies of irrigation water or settlement on newly developed irrigation schemes (Wester *et al*., 1995). The effect of the investment in irrigation projects are immediately visible in the form of newly constructed farms, canals and developed lands. However, the maturing of the social and economic complex initiated within the communal irrigation project development often takes years to happen. Along with the irrigation development, the local government has a vital role to play, mainly in providing important infrastructure such as roads and schools, and possibly assisting in the provision of medical and recreational facilities (Thorne & Peterson, 1950). In turn, it helps the society in providing social stability and economic sustainability, depending on the continuous and intensive monitoring and maintenance of the project.

Regarding the administrative aspect of irrigation, it is vitally important to consider the type of organisations formed to deliver irrigation water. The relationship between the organisation and water users and their legal powers is governed by these kind of organisations. Failures could be anticipated in good projects as wrong organisations are adopted. Hansen *et al.* (1980) reported that the most successful enterprises have been those owned and operated by water users and, when the water users are directly involved, their interest is keen and their services are rendered at a minimal cost.

In the planning and operation of irrigation projects, consideration of the social and economic aspects of the farming community is becoming increasingly important, mainly in developing countries. In such countries, farmers participating in irrigation water management might have been involved in ordinary or mixed agriculture and require strong guidance before they can be expected to make a significant contribution

to the project. Several experiences in many parts of the world have shown that overlooking these issues has definitely affected the tangible and qualitative success of irrigation enterprises (Hansen *et al.*, 1980). It was repeatedly proved that the success of irrigation enterprises was the product of the careful use of a well-designed system by well-trained and equipped farmers. In this regard, the selection of appropriate farmers and the provision of training and other assistance will ensure the sustainability of the project. However, the degree of assistance given to a farmer varies, depending on the criteria used during the selection. In many countries, the assistance rendered to irrigation communities include improved agronomic practices, a supply of improved crop and animal species, microfinance credits and marketing. Here, the strong commitment of local governments is decisive in promoting marketing situations and especially collecting their dues in kind at farm-gate price when prices of commodities fall excessively. It is crucial that the government manages the adverse effects of irrigation, like environmental pollution, outbreak of malaria, parasitic weeds and diseases as part of regional health mitigation programmes (Hansen *et al.*, 1980).

The efficiency and sustainability of community-based water management systems were investigated at several pilot project schemes. The performance of various pilot schemes varies depending on the size and design of irrigation systems, socio-political perspectives, cultural values, agricultural practices and the status of existing administration. It is imperative for a pilot scheme to be truly representative, replicable and backed up with independent evaluation of its performance over a sufficient period.

The improvement of traditional small-scale irrigation schemes does not end only at the placement of a well-structured water users' association or the involvement of water users in the management of irrigation water, but also requires improvement of the water use efficiency of available water resources.

2.2 Water management and irrigation scheduling

Improving traditional small-scale irrigation schemes is not adequately performed by only involving the water users in the management of irrigation water, but also requires improving the water use efficiency of the scarce water resource. Traditional irrigation is mostly characterised by deteriorated irrigation networks that cause high water losses and the use of rudimentary methods to control water wastage and poor crop productivity (Waskom, 1994). These factors, coupled with the lack of appropriate water management technology has caused traditional irrigation schemes to keep on producing low yields (Waskom, 1994). Hence, the improvement of traditional irrigation schemes requires all-round interventions, starting with involving the community in the system management up to improving of water-measuring structures and supplying options for when and how much water to apply. With regard to the furrow irrigation system, the issue of when to irrigate and how much water to apply refers solely to the supply of a working irrigation schedule, depending on the ability of the community to practice (Raghuwanshi & Wallender, 1998).

2.2.1 Irrigation scheduling methods

Traditional irrigation farmers have been practicing their own scheduling methods since the inception of irrigated agriculture. At present, traditional irrigation scheduling, coupled with low yielding crop cultivars, remained solely subsistent and

not economically feasible. Most of the traditional irrigation schedules are dependent upon monitoring the crop canopy, which only allows the farmer to decide when to irrigate (Waskom, 1994). The amount of water to be applied depends on the availability of the water resource, which may not vary between either the crop species or their growth stages. At present, however, scientific irrigation scheduling has developed to overcome various irrigation problems, where it helps the farmer to determine the exact amount of water to apply to the field and the exact timing of application (James, 1988). The amount of water applied is determined by using a criterion to determine irrigation need and a strategy to prescribe how much water to apply in any situation (James, 1988). Hence, the importance of irrigation scheduling is to enable the irrigator to apply the exact amount of water to achieve the goal and increase irrigation efficiency (James, 1988). The same author also explains that irrigation scheduling improves crop yield and quality, and conservation of water and energy, resulting in lower production costs.

Irrigation scheduling methods vary depending on the objective of individual farmers. Proper irrigation scheduling, based on timely measurements or estimation of soil water content and crop water needs, is one of the most important aspects of irrigation management (Waskom, 1994). Monitoring soil water in the crop root zone will allow better management of water application to the requirement of the crop. However, direct measurement of soil water in the field is tedious, mainly at large-scale production levels. At present, there are a number of devices, techniques and computer aids available to assist producers when to apply and how much water is required by a particular crop at a given growth stage (James, 1988). Even though each farmer envisages different goals in irrigation scheduling, they all have one goal in common,

which is selecting a water management strategy that allows them to prevent over-application of water, while maximising the net return (Waskom, 1994). Many water balance approaches have been used to determine water availability to the crop and irrigation scheduling. However, few approaches consider crop development, from sowing to harvesting, through plant and soil evapotranspiration (ET) (Annandale *et al.,* 1999). Most of the time, calculations are based on potential ET values, estimated by locally tested formulae or, at best, on the Penman generalised expression (Tuzeti *et al.*, 1992).

According to Waskom (1994), irrigation-scheduling methods are grouped into three major categories, namely soil water monitoring, crop canopy index and the water budget approach (Table 2.1).

Table 2.1 Irrigation scheduling methods, tools required and the advantages and disadvantages of each method (Waskom, 1994).

Methods	Tools or parameters used	Advantages/Disadvantages
I. Soil water monitoring (Indicates when and how much to irrigate)		
Hand feel & appearance	Hand probe	Variable accuracy, requires experience
Soil water tension	Tensiometers	Good accuracy, easy to read, but narrow range
Electrical resistance tester	Gypsum block	Work over large range, but limited accuracy
Indirect soil water content	Neutron probe/TDR	Expensive, and requires many regulations
Gravimetric analysis	Oven and scale	Labour-intensive
II. Crop canopy index (Indicates when to irrigate, but not how much to apply)		
Visual appearance	Field observation	Variable accuracy, depending on the experience of the farmers
Water stress index	Infrared thermometer	Expensive
III. Water budget approach (Needs periodic calibration since it estimates the water use)		
Checkbook method	Computer/calculator	Indicates when and how much water to apply
Reference ET	Weather station data	Requires appropriate crop coefficient
Atmometer	Weather station data	Requires appropriate crop coefficient

Most of the soil water monitoring methods and devices do not measure soil water directly; they measure a property of the soil that is indirectly related to soil water status, and hence, these methods differ in ease of use, reliability, cost, and the labour requirement (Evans *et al.*, 1996). In all three of the broad categories of scheduling, however, the user has to have the knowledge of soil water holding capacity, the current available soil water content, the crop water use and effective root zone depth (Broner, 2005).

According to Al-Kaisi & Broner (2005), significant evaporation can take place only when the soil's top layer or the plant canopy is wet. Once the soil surface is dried out,

evaporation decreases sharply. Thus, significant evaporation occurs after rain or irrigation. Furthermore, as the growing season progresses and the canopy cover increases, evaporation from the wet soil surface gradually decreases. When the crop reaches full cover, approximately 95% of the ET is due to transpiration from the crop canopy. At this growth stage, the crop canopy intercepts most of the incoming solar radiation, thereby reducing the amount of energy reaching the soil surface (Al-Kaisi & Broner, 2005). Crop water use (ET) is influenced by prevailing weather conditions, available water in the soil, crop species and growth stage. At full cover, a crop will have a maximum ET rate if soil water is not limited and the soil root zone is at field capacity. Soil characteristics are mainly influenced by soil texture, organic matter content, soil structure and permeability, which further limit producers' management and system options.

Crop root depth is primarily influenced by plant genetics, restrictions within the soil horizon and the maturity stage of the crop. Such circumstances create substantial management problems, especially with furrow/flood irrigation systems (Jones, 2004). Most surface irrigation systems have inherent inefficiencies due to deep percolation on the upper end and run-off at the lower end of the field, unless careful management decisions are involved (Jones, 2004). Efficient irrigation results when design and management enable producers to uniformly apply enough water to fill the effective crop root depth with minimal run-off. The correct amount of water applied at each irrigation varies due to changes in root depth, soil water status and the soil intake rate (Waskom, 1994). Waskom (1994) also indicates that irrigation set size, stream size, set time and the length of run can be optimised by irrigators to improve efficiency, that is, a well-designed and properly-managed surface system can attain efficiencies of 60% or better.

Identifying crop sensitivity to water stress at current growth stages, recording effective rainfall between two irrigations and the availability of water supply, help the user to make useful decisions (Raghuwanshi & Wallender, 1998). The same authors also emphasise the decision on irrigation, which should mostly be based upon an estimate of crop and soil water status, coupled with some indication of economic return. Hence, such proper scheduling allows producers to reduce the traditional number of irrigations, thereby conserving water, labour and plant nutrients (Waskom, 1994; Evans *et al.,* 1996; Papajorgji & Shatar, 2003; Broner, 2005).

Scheduling irrigation applications are often accomplished by using root zone water balance approaches (Waskom, 1994; Evans *et al.,* 1996), which uses the Checkbook or budgeting approach to account for all inputs and withdrawals of water from the soil (Scherer *et al.*, 1996; George *et al.*, 2000; Jones, 2004). The concept of root zone water balance approach is illustrated in a mathematical expression in equation 2.1 (Waskom, 1994):

$$I+P = ET+Dr+Ro \pm \Delta S \qquad (2.1$$

where I = irrigation water applied, P = precipitation, ET = evapotranspiration, Dr = drainage of water percolation below the root zone, Ro = run-off; ΔS = change in soil water content

Many irrigation-scheduling methods provide the users good cost-effective, but may be too sophisticated to apply. For traditional irrigation users, however, water saving and cost-effectiveness alone should not be the only consideration for irrigation scheduling; it should be simple to understand and apply, and financially affordable.

2.3 Cultivation of some economically important crops under traditional irrigation

The dry period for most Ethiopian regions commences at the beginning of October to the end of May. During this period, short rainfalls occur in some parts of the country that cannot maintain crop production without supplementary irrigation. Most tree crops and medicinal perennial crops require supplementary irrigation during this period that would carry them through to the main rainy period. The high-value vegetable crops, however, require full irrigation, as the distribution of existing rainfall does not suffice the more frequent water demand of these shallow rooted crops. These crops include onions, tomatoes, potatoes, peppers, cabbages, lettuce, etc. In this study, only the cultivation of potatoes and onions by means of the traditional irrigation method is assessed.

2.3.1 Potatoes

Origin and history

Potatoes (Solanum tuberosum) originated in South America. Its native home is often claimed to be the Andean region of Peru and Bolivia, where the Incas cultivated the plant mainly for food. In these regions, the potato's close botanical relatives still flourish and make the gene pool abundant for improvement (Brown, 1993; Rolot & Seutin, 1999). Potatoes are highly diversified by their nature and, at early human settlement in the highlands of Bolivia; men started to select suitable cultivars for food. Potatoes are believed to have been introduced to Europe by the Spanish conquest in the 16th century and remained a botanical curiosity until it was popularised by Antoine-Augustine from 1780 onwards Smith, 1968 (Rolot & Seutin, 1999). It was

taken to the United States in 1719 by Scottish-Irish settlers and, during the 19th century, thousands of varieties originated by plant breeders, among which only small numbers were accepted for large-scale production (Smith, 1968). Potatoes were introduced to Africa as recently as the end of the 19th century. The improved species of South American clones that were co-ordinated by the Centro Internacional de la Papa (CIP) in Peru have helped to introduce a wide range of adaptability worldwide.

A fresh potato contains about 80% water (SFC, 1992). The solids or dry matter are highly correlated with texture. Mealy textures are usually associated with high solids, while waxy textures are usually associated with low solids. Although individual tastes may vary greatly, varieties with high mealy texture are usually considered best for baking or french-frying. On the other hand, varieties that are of waxy texture are more often used for boiling or in salad. Potatoes are a rich source of carbohydrates and contain valuable amounts of protein, minerals and vitamins. The nutrient level varies not only by variety, but also according to the maturity of the crop and storage time (SFC, 1992).

Climatic requirements

The wild species of potatoes with some food value survive on the snow line as high as about 4 800 m and are more resistant to frost than the modern varieties (Smith, 1968). Potatoes grow in a wide range of climatic conditions and altitudes. In tropical Africa, it does well between 1 800 and 2 300 m as the climate is tempered by altitude, or at lower altitudes during the cool seasons (Smith, 1968; Brown, 1993; Rolot & Seutin, 1999). Potato vine growth is enhanced by day temperatures of more than 27°C as well as by night temperatures higher than 23 ^{o}C. Vine growth is further enhanced by long

days, while short days stimulate the production of tubers. Low night temperatures of about 16°C are ideal for tuberisation, up to as high as 29°C of day temperatures, above which tuber formation could be inhibited (Struik *et al.,* 1997). The ideal environment that stimulates flowering usually promotes the development of tubers.

Yields are usually lower in eastern tropical Africa than in temperate zones. It could be attributed to the detrimental effect of short day length and high air and soil temperature (Smith, 1968; Bradley *et al.,* 2005). Besides the night-time temperature, photoperiod plays an important role in tuberisation, which is triggered when the daylight falls below a certain critical threshold. Under short day-length conditions, tubers are initiated much earlier than under long-day conditions, making tuberisation more abrupt and leading to maturity much faster. Despite this, the origin and early cultivation of potatoes began in the Andes where the days are short throughout the year and where potatoes are especially adapted to short-day conditions. Smith (1968) suggests that short days hasten maturity, reduce growth of tops and increase the efficiency of tuber formation. However, it is more convenient and faster to develop European long-day cultivars under short-day conditions, especially for the production of commercial planting materials.

When long-day material is put under short-day conditions, it will undergo some physiological changes, namely stem elongation will terminate earlier, tubers initiate earlier and plants die earlier than under long-day conditions. In addition, the mass of leaves and stems, as well as the number of leaves per stem would be lower, while leaflets are larger (Brown, 1993; Struik *et al.,* 1997).

The ratio of leaf-stem mass is higher under short-day than under long-day conditions. Tuber mass is comparably higher in the early development stage under short-day conditions. However, when cultivars with a long maturity period are grown under long-day conditions, it attains a higher final production despite its later tuber initiation. Overall, the critical day length is severely influenced by temperature and light intensity and it decreases with an increase in temperature or a decrease in light intensity (Smith, 1968).

At low light intensity, tuber mass is higher at an average temperature of about 12°C. Optimum tuber mass occurs with higher light intensity and temperatures higher than about 18°C. However, tuber growth is most favoured by high day temperatures (18-24°C) and low night temperatures of about 17°C. The number of tubers decreases with increasing night temperatures. A high night temperature favours more growth above the ground than underground, during which plants develop many new leaves, many branches, and flowers. Under such conditions, stolons emerge above the soil, form new stems and leaves and result in a low tuber yield with a small number of tubers. At low temperatures, however, more growth occurs underground than above ground, where plants form a small number of leaves, few or no branches, no flowers, no stolons above ground, but a large number of tubers resulting in a high tuber yield.

Soil and water requirements

Selection of the right soil type is very important for potato crop production. Potatoes are shallow-rooted and sensitive to water stress. Hence, well-drained light-texture soils, such as sandy loams or loamy sands are generally suitable for the production of a high yield of good quality potatoes. Such soils can store large amounts of water and

nutrients, even though any soil can become unproductive under poor management. Soils with good structure are loose and friable and the surface of these soils does not form a crust so that they remain open for air and water for further circulation in the crop root zone (Smith, 1968; Brown, 1993).

Potatoes should preferably not be planted in heavy soils. Under water logging conditions, the chemical reaction necessary for maintaining a proper environment for potato roots cannot take place and, when air is excluded, plant materials cannot decompose properly and the potato root cannot grow vigorously. When heavy soils are used, artificial drainage facilities need to be provided and an incorporation of organic matter also makes a big improvement. Studies conducted by Brown (1993) and Struik *et al.* (1997) confirm that potato yields increase as organic matter and bulk density on Caribu soils increase. Organic matter is important for most crops in general and for potatoes in particular. The ideal potato soil contains up to 3% organic matter, which helps in maintaining its granular structure (Smith, 1968). Organic matter is best maintained under well-mixed crop rotations. Potatoes are usually grown in rotation with other crops to maintain desirable soil structure, fertility status, build-up organic matter, reduce crop loss from insect and disease, and to increase yields (Smith, 1968). Many potato growers follow a crop rotation of not more than two years of potatoes, one year of small grain and one year of grasses. Soils under such rotation would have a good granular structure, high water-holding capacity, adequate aeration, and abundant available plant nutrients. Organic matter usually facilitates ploughing and cultivation, enables potato plants to penetrate the soil readily, retains soil water, provides food for the growth of desirable micro-organisms, and supplies plant nutrients to the crop (Smith, 1968; Brown, 1993). Potato tubers develop and maintain

their normal shape better in soils with adequate organic matter. In conditions where continuous potato growing is desired, a breaking cover-crop should at least be seeded just after harvest (Smith, 1968; Brown, 1993).

Soil reaction is one of the important factors affecting the availability of various soil constituents and the absorption of available nutrients by the crop (Mengel & Kirkby 1982). Smith (1968) indicates that a certain relationship exists between soil reaction and rate of plant growth and development, tuberisation, and chemical composition of the potato. Results from potato crops planted on various soil reactions revealed that lower yields of plants grown on high pH were due to the accumulation of large amounts of calcium salt that resulted in a low supply of available manganese. The ideal soil reaction for potato growth and development is between 4.8 and 5.5 pH. In soils with a pH of 5.5 to 7.0, potatoes can be subjected to scab diseases. Potatoes are the only crop that loves soil reaction as low as 4.8 pH (Smith, 1968).

Potatoes respond well to both organic manure and mineral fertiliser applications. Most potato growers practise organic manure application at the rate of 20-30 t ha^{-1}. Chemical fertiliser application depends on the nutrient content of the soil, considering the heavy requirement of potash fertiliser by potato crops (McLaurin *et al*., 2002). The application of nitrogen and potassium is a determining factor of the qualitative and quantitative production of potatoes. An excess application of nitrogen may delay maturity of the crop, impair quality of the tubers and/or adversely affect their storage (Smith, 1968; Brown, 1993; Struik *et al*., 1997).

Potatoes require irrigation where soil water availability is not consistent through all the growth stages. High yield, earlier production and drought protection are the advantages of irrigating potatoes. Potatoes can be influenced critically with uneven water supply, affecting the development of knobs or growth cracks on the tubers. The plant does not use much water early or late in the season, but needs a lot of water when foliage is fully developed. According to the SFC (1992), the potato plant requires about 460-720 mm of water to mature. However, the frequency and amount of irrigation of the crop depend on the soil type, method of irrigation, the crop growth stage and the evaporative demand. In general, heavier soils need irrigation of adequate depth once a week, but more frequent irrigations may be necessary in the case of sandy soils. An ideal potato water management programme is to limit the wetting depth to the effective root zone, which is about 0.6 m, and the soil should not be allowed to dry below 65% of field capacity. On the other hand, soil water levels above field capacity will seriously affect yield and quality. Sprinkler-irrigated potatoes benefit from light, but frequent three to five day applications, especially when temperatures are higher than 26°C. Irrigation should be reduced when the plant leaves begin to turn yellow and the plant starts to die. Too much water at maturity stage may predispose tubers to rot and vines need to be dead at least one week prior to harvesting. Generally, withholding water late in the growing season will help potatoes to store better (SFC, 1992).

The sensitivity of potatoes to water stress varies with the crop growth stage and to some extent, the cultivar. During tuber initiation, water stress could reduce the number of tubers produced per plant. During tuber bulking, however, tuber size and quality are closely related to water supply. Research has shown that the total yield of

potatoes are most sensitive to water stress during mid-bulking, which occurs three to six weeks after tuber initiation, and water stress any time during this period will have a severe effect on the total yield (SFC, 1992). Furthermore, tuber growth is retarded by water stress and does not resume uniformity when water is replenished again. Under such conditions, new growth and enlargement will take place at the top stem end, while the other portions of the tuber remain stunted. In some potato varieties, tubers develop some constricted areas that are related to the stage of tuber growth at the time the water stress occurred. Other deficiencies in quality such as growth cracks and knobbiness are also related to water stress followed by periods of adequate or surplus soil water.

Planting and cultivation

The ideal planting depth for potatoes is about 10 cm deep. However, in areas where soil water is a limiting factor, the depth could go up to 13 cm. Potatoes are planted from seed pieces and the seed rate varies depending on seed piece size, the varietal characteristics and desired plant spacing (Scherer *et al.,* 1999). A spacing of 23-30 cm between plants is generally practised in most countries. A wider spacing (25-30 cm) is required for varieties with a heavy tuber set, smooth tubers and varieties resistant to the development of hollow heart and deformities. A closer spacing (20-25 cm) is recommended for varieties with poor tuber set to reduce the number of oversized tubers (Scherer *et al.,* 1999). The seeds are mostly cut into seed pieces for planting, even though whole seed is less sensitive to tuber decay. Cut seed pieces should be firm and with at least one or more eyes to secure germination and plant establishment. Plants from small seed pieces are generally slower to emerge and are less vigour ones.

Soil temperatures should be between 7-21°C at planting; as planting into cold soils delays emergence and increases the risk of seed piece decay (Scherer *et al.,* 1996).

The growth and development of potatoes are divided into four stages (Hayes & Thill, 2002).

The vegetative stage: This stage of growth begins when the seed breaks its dormancy and produces sprouts. This process usually requires 15-30 days, depending on the cultivar and temperature in the area.

Tuber initiation: This stage commences with the tuber initiation at the tip of stolons and takes approximately 10-14 days.

Tuber bulking: This is a stage where tubers are constantly increasing in size and mass. This stage usually lasts 60 to more than 90 days, depending on the length of the growing season and external factors such as the presence of pathogens.

Maturation: This is the stage where potato canopies begin to senesce in general and older leaves gradually turn brown and die. This condition generally spreads to the remaining plant parts, such as vines and younger leaves that lead to the final death of the crop. This stage is associated with less or no tuber growth and the crop is ready for harvest, depending on the purpose of production.

After planting, potatoes may be cultivated to control weeds and to reshape the beds. Potatoes are commonly hilled when they attain a height of 20-30 cm and soil is mounded around the plant base to prevent greening or sunburning of tubers. Potatoes are vulnerable to pests and diseases. Besides using certified seeds, it is also important to maintain proper soil fertility and water management, frequent sanitation and crop rotation and the use of resistant varieties.

Harvesting and storage

The harvesting of potatoes varies depending on the variety and the intended marketing. Potatoes may be harvested with vines still green and tubers comparatively immature when it is intended for immediate use as new potatoes. Most potatoes, however, are harvested at full maturity when their skins are set, they are big enough in tuber size and their vines have died. Mature tubers store better than immature tubers and resist bruising better.

Storage of potatoes is often complicated by the interdependence of light, heat, moisture, potato injuries and length of storage period. Storage temperatures are adjusted depending on the intended purpose of the tuber and length of storage period (Edgar, 1968). Temperatures above 21°C are hazardous immediately after harvest, but advantageous for conditioning after long storage under low temperature. The ideal storage temperature is around 16°C for about 90 days after harvest at 90% relative humidity (RH) before tubers start to sprout, and can be prolonged for about 6 months if sprout inhibiters were used (Edgar, 1968; Struik *et al.,* 1997). Despite this fact, other researchers agree that storage at 21°C for the first three weeks results in reducing sugar, which is inversely proportional with chip quality (Smith & Davis, 1968). Potato storage conditions could vary depending on environmental complex and altitude. For tropical Africa, researchers agree that the ideal storage temperature would be from 2°C to 3°C for seed potatoes and from 6°C to 8°C for tubers for consumption (Rolot . *et al.,* 1983; Struik *et al.,* 1997).

Prolonged exposure of potatoes to sun or artificial light under storage causes greening of the tuber skin and tissue, and it becomes unfit for food. However, the greened

tubers are not discriminated against for seed purposes. Generally, potatoes require ideal temperatures, humidity and adequate ventilation for minimum storage loss of yield and quality.

2.3.2 Onions

Origin and history

Onions (*Allium cepa* L.) are believed to have originated in west or central Asia and are small crops growing in association with other crops. For this reason, there is no conclusive opinion about the exact time and location of their origin. However, many researchers agree that onions originated in central Asia. Since onions are grown in a wide range of climates from temperate to tropics, they were probably consumed for thousands of years and simultaneously domesticated all over the world (Ehler, 2005). Onions may be one of the earliest cultivated crops because they were less perishable than other food crops, easily transportable, easily grown and produced in a variety of soils and climates. Even though the place and time of the onion's origin are not clear, there are many documents from early times which describe its importance as a food and its use in art, medicine and mummification.

Onion is a cool season biennial monocot with a prominent bulb, hollow cylindrical leaves and a strong odour when bruised (Casey & Garrison, 2003). The crop is said to be tolerant to frost. The optimum temperature for plant development varies between 13°C and 24°C, while, for raising seedlings, it requires up to 20-25 ^{o}C and generally require high temperatures for bulbing and curing (Kalb & Shanmugasundaram, 2001). The bulb onion cultivars are classified into three groups, depending on day lengths. The short-day onion cultivars are characterised by thresholds of 12-13 hours, the

intermediate by 13.5-14.5 hours and the long-day cultivars by over 14.5 hours. If any of the groups go out of its range for cultivation, it will not form bulbs or it will form small bulbs, a little more than sets in size.

Soil and plant nutrient requirements

Onions grow on a variety of soils ranging from sand to clay loams. However, they prefer loamy soil that is fertile, well drained and high in organic matter, with a preferable pH range of between 6.0 and 6.5 (Sanders, 1997). Onions do not thrive in soils below pH 6.0 because of trace element deficiency, or occasionally, aluminium or manganese toxicity. Onions could be produced on slightly alkaline soils, but are sensitive to soil salinity. According to the FAO (2002), a soil salinity level of 4.3 dS m^{-1} could decrease the yield of onion by up to 50%.

Onions differ widely in plant nutrient consumption, depending on production history, soil type and the target of production. Generally, onions prefer soils with a high organic matter or an application of organic manure at the rate of 25-40 t ha^{-1} for high bulb yield production. The nutrient element in manure becomes available to plants over an extended period and the organic material in manure improves soil structure, while also helping to make other fertiliser elements more readily available to the plant (Corgan *et al.,* 2000). In conditions where mineral fertilisers are to be used, applications are practised, either as a broadcast or, more commonly, as a band dressing a few centimetres directly under the seed set or transplant. This crop usually requires a substantial dose of nutrients. According to Kalb and Shanmugasundaram (2001), onions with a bulb yield of 18 t ha^{-1} remove an average of 66, 11 and 70 kg ha^{-1} of N, P and K nutrients respectively. Some pre-plant nitrogen, usually about 120

kg ha^{-1} (Corgan *et al.,* 2000), is needed as a starter fertiliser to avoid losses through either leaching or volatilisation while the plant roots are not developed enough to absorb the bulk application. After plant establishment, one or two side dressings of nitrogen are required during the season. Insufficient nitrogen will induce early maturity and reduce bulb size, while high nitrogen may increase bulb size, but cause large nicks and soft bulbs with poor storage quality. Crop rotation has a more multi-beneficiary effect on onions more than on most other crops. Rotation helps to maintain good soil structure, resulting in improved crop growth, decreased incidence of pathogens causing disease and aid in weed management. In addition, crop rotation helps in balancing plant nutrients, as onions planted following legumes could benefit from nitrogen residues (Corgan *et al.,* 2000). In general, phosphorus fertilisers are applied before onion crop planting. Some soils may have a sufficient phosphorus content, but adhering to the available portion is required.

Water requirements

Onions require frequent irrigation throughout the growing season for several reasons. The root system is shallow, therefore, very little water is extracted from a soil depth deeper than 0.6 m, and most is from the top 0.3 m (Voss & Mayberry, 1997). Onion roots are mostly non-branching and all roots originate at the stem, or basal plate of the plant. This indicates that upper soil areas must be kept moist to stimulate root growth. Rates of transpiration, photosynthesis and growth are lowered by even mild water stress. Onions show little capacity for reducing leaf water potential by osmotic adjustment to compensate for reduced water availability at the root (Voss & Mayberry, 1997). Fields that frequently experience water stress would suffer growth retardation and produce excessive numbers of doubles or splits, reducing the number

of grade one bulbs (Kalb & Shanmugasundaram, 2001). For optimum yield, onions require 350-550 mm of water, but may use more than that in tropical areas where ET is appreciably higher (FAO, 2002). However, onions are best grown when the managed allowable depletion is maintained above 70% of the total available water, after which a yield reduction will occur (Corgan *et al.,* 2000; FAO, 2002).

Managing the time and amount of applied irrigation is critical to achieve optimum yield and quality. Light and frequent irrigations are required through furrow, sprinkler or drip irrigation systems. Irrigation frequency varies with the planting time of the year, the size and development stage of crop, and the irrigation system used (Corgan *et al.,* 2000; FAO, 2002). Sprinkler irrigation is preferred during germination and early crop development, so that it permits small but frequent amounts and also deliver water to areas that are not levelled. Either drip or furrow irrigations are recommended at the latter stage of plant growth, as there is increasing concern that sprinklers are wetting the foliage, thereby promoting foliage diseases and subsequent increases in bulb disorders (Corgan *et al.,* 2000). In general, the choice of irrigation system depends on each individual merit of the system and the contrasted economic feasibility that must be the preferences of individual farmers.

Harvesting and storage

Onions are harvested when 80% of the bulbs become completely mature, which is evident by the collapse of the neck tissue and falling of the tops. After harvesting, the roots are trimmed and the tops cut away. Bulbs are usually put into an appropriate case and allowed to cure outdoors. After bulbs are properly cured, onions are graded according to the individual standards of the country. According to the USDA

standard, onions are graded for size and shape, proper maturity and firmness. Onions must also be free of splits, seedstems, dry sunken areas, roots, tops, translucent or watery scales, moisture, disease and insects (Corgan *et al.,* 2000).

Harvested onions are dormant and will not sprout for a long period, depending on the cultivar. Storage conditions are an important factor in prolonging the dormancy. During storage, the sprouting of onions is most favourable between temperatures of 4°C and 25°C. For prolonged storage, onions may be treated in the field with maleic hydrazide (MH-30) at the rate of 2.2-3.4 kg ha^{-1} when the tops are still green but beginning to senesce (Kalb & Shanmugasundaram, 2001).