SOIL-WATER DYNAMICS, ROOT GROWTH AN WHEAT YIELD IN A SEQUENTIALLY DEEP TILLED POST-RICE SOIL

THESIS

By

ANIL MAHAJAN

Submitted to

CHAUDHARY SARWAN KUMAR
HIMACHAL PRADESH KRISHI VISHVAVIDYALAYA
PALAMPUR (H.P.) – 176 062 INDIA

IN

Partial fulfillment of the requirements for the degree

OF

DOCTOR OF PHILOSOPHY IN AGRICULTURE
(SOIL SCIENCE)

2005

DEDICATED TO MY BELOVED MAMA JI

LATE Sh. HIRA LAL CHADHA

WHO HAD BEEN A SOURCE OF CONSTANT

INSPIRATION

AND

ENCOURAGEMENT

IN MY

LIFE

Dr. R. M. BHAGAT
Programme Director

Centre for Geo-informatics Research and Training
CSK HP Krishi Vishvavidyalaya
Palampur (H.P.) - 176 062 INDIA

CERTIFICATE – I

This is to be certified that the thesis entitled, **"Soil-water dynamics, root growth and wheat yield in a sequentially deep tilled post-rice soil"** submitted in partial fulfillment of the requirements for the award of the degree of **Doctor of Philosophy (Agriculture)** in the subject of **Soil Science** of Chaudhary Sarwan Kumar Himachal Pradesh Krishi Vishvavidyalaya, Palampur, is a bonafide research work carried out by **Mr. Anil Mahajan** (Admission No. A-2001-40-20) son of **Sh. Arvind Mahajan,** under my supervision and that no part of this thesis has been submitted for any other degree or diploma.

The assistance and help received during the course of this investigation have been fully acknowledged.

(R. M. Bhagat)
Chairman
Advisory Committee

Place: Palampur (H.P.)
Dated: the 10th November, 2005

CERTIFICATE – II

This is to be certified that the thesis entitled, **"Soil-water dynamics, root growth and wheat yield in a sequentially deep tilled post-rice soil"** submitted by **Mr. Anil Mahajan** (Admission No. A-2001-40-20) son of **Sh. Arvind Mahajan** to the Chaudhary Sarwan Kumar Himachal Pradesh Krishi Vishvavidyalaya, Palampur in partial fulfillment of the requirements for the award of the degree of **Doctorate of Philosophy (Agriculture)** in the subject of **Soil Science** has been approved by the Advisory Committee after an oral examination of the student in collaboration with an External Examiner.

(Dr. R. M. Bhagat)
Chairman
Advisory Committee

6.1.06
External Examiner

06/01/06
(Dr. T. S. Verma)
Member

6-1-06
(Dr. H. L. Sharma)
Member

6/1/06
(Dr. R. K. Dohru)
Member and Dean's Nominee also

6/01/06
(Dr. T. S. Verma)
Head
Department of Soil Science
CSK HPKV, Palampur

(Dr. B. Prasad) 12/01/2k6
Dean
Postgraduate Studies

ACKNOWLEDGEMENT

With limitless humility, I would like to praise and thank God, the supreme and merciful, who blessed me with all the favourable circumstances to go through this gigantic task; and bestowing me with such affectionate parents, whose heartfelt blessings and constant encouragement has always been a source of inspiration to me to burge and pursue for excellence.

It is my privilege to express my sincere gratitude to my most respected and revered teacher Dr. R. M. Bhagat, Programme Director (GIS) and the chairman of my advisory Committee for suggesting such an interesting problem of practical utility. His knowledgeable guidance, concrete suggestions and constructive criticisms with his scientific acumen during the course of this study steered the completion of his dissertation.

I feel great pleasure to convey my sincerest thanks to the esteemed members of my Advisory Committee Dr. T.S. Verma, Dr. H.L. Sharma, and Dr. R.K. Dohru for their valuable suggestions and painstaking efforts during the whole course of the study.

I must put on record my special thanks to Dr. Sharada Singh (Associate Professor), Dr. Chitra Sood (Project Scientist), Dr. Ranbir Singh Rana (Assistant Scientist) and Mr. Vaibhav Kalia (Assistant Professor), Centre for Geo-informatics Research and Training for their generous help during the investigation.

I feel honoured in express my sincere thanks to Dr. T.S. Verma, Sr. Soil Scientist and Head, Department of Soil Science for providing necessary facilities and *support during the course of my study. I am also thankful to the members of faculty, field, laboratory and ministerial staff of the Department of Soil Science for their cordial co-operation and encouragement during this period.*

I am also thankful to Dr. B. Prasad, Dean, Post Graduate Studies, CSK Himachal Pradesh Krishi Vishvavidyalaya, Palampur for providing necessary facilities.

It please me much I think of acknowledging the nice and timely help of my friends Ruchi, Usha, Amit, Ankur, Pankaj, Rohit, Shashi, Sanjay, Ajay, Susheel, Naresh, Vishal, Gurpreet, Sudhir, Rathore, Rajiv, Anurag, Samshar and Adarsh for their instinctive help, guidance, suggestions and encouragement during the various stages of my current study.

I shall be failing in my duty if I do not acknowledge the facilities provided to me by my almamater, CSK HPKV, Palampur. The financial assistance in form of university merit scholarship is also duly acknowledged.

I can never forget the constant inspiration and support given by my Guru ji Sadhu Ram Masand, gracious father Sh. Arvind Mahajan, affectionate mother Smt. Parkash Gupta, loving brother Mr. Narinder Mahajan, sister Archana Gupta, Kamlesh and Manju, brother-in-law Dr. Mrityunjay Gupta, uncle(s): Sarvir Singh Jamwal and Puspinder Singh Jamwal and nephew Pranshu.

Needless to say, all errors and omissions are mine.

Anil Mahajan

(ANIL MAHAJAN)

Place: Palampur (H.P.)
Dated: the 10th November, 2005

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

INTRODUCTION

CHAPTER-I

INTRODUCTION

The word tillage is derived from the Anglo-Saxon words tilian and teolian, meaning to plough and prepare soil for seed to sow, to cultivate and to raise crops. Generally, it is the mechanical manipulation of soil for obtaining conditions ideal for seed germination, seedling establishment and growth of crops. The purpose of tillage is to obtain a seedbed having optimum soil tilth, break weed, insect and diseases cycles, bury plant residues, incorporate fertilizers and amendments, break surface crust and fracture plough pans or hard subsoil horizons (Jones *et al.*, 1990).

In modern times, soil tillage has emerged as an integral part of a crop system. Soil tillage and soil surface management have been found important in alleviating soil related constraints encountered in crop production. An important effect of soil tillage on crop productivity is through its influence on soil processes, soil properties and crop growth. At the same time, soil tillage has its impact on the environment e.g. soil degradation, water quality, emission of green house gases from soil related processes etc. The need to attain self-sufficiency in agriculture production has been particularly urgent in several tropical eco-regions and soils of low carrying capacity in the tropics. Appropriate tillage systems are soil and crop specific and their adoption is governed by both bio-physical and socio-economic factors. In addition to increasing crop yields, tillage methods must also facilitate soil and water conservation, improve root system development and maintain a favourable level of soil organic content (Lal, 1991).

The rice-wheat is the principle cropping system occupying 24 million ha of cultivated land in the Asian subtropics. In South Asian countries, the system is prevalent in about 13.5 million ha in the Indo-Gangetic Plains (IGP) of 10 million ha in India, 2.2 million ha in Pakistan, 0.8 million ha in Bangladesh and 0.5 million ha in Nepal and about 10.5 million ha in China. This system covers about 32 per cent of the total rice area and 42 per cent of the total wheat area in these four countries (India, Pakistan, Bangladesh and Nepal) and account for one quarter to one third of the total rice and wheat production (Ladha *et al.*, 2000). It provides food, income and employment for millions of people. The annual system productivity in IGP is low (3-5 Mg ha^{-1}) as compared with the climatic crop yield potential of the region i.e. 12.0-19.3 Mg ha^{-1} (Ladha *et al.*, 2003a; Pathak *et al.*, 2003a). The rice-wheat system is pivoted to food security not only of the country but also of Indian subcontinent as a whole. The ten-fold increase in rice-wheat sequence in India, Nepal, Bangladesh and Pakistan during the last 30 years is an ample proof of it (IRRI, 1992). Further, rice has been grown as a food crop for more than 6,000 years in Asia. Today more than 90 per cent of global rice supplies are produced and consumed in Asia, contributing 30-75 per cent of dietary calories for populations in these countries (Dobermann and Cassman, 1996). About half of the irrigated wheat production in South Asia comes from rice-wheat rotation (Pillai, 1994).

The rice-wheat is the most extensive and traditional cropping system in India which has become the main stay of cereal production in the country. It occupies 10.5 million ha area, dominates agricultural systems in India mostly in Punjab, Haryana, Uttar Pradesh and Madhya Pradesh (Yadav and Subba Rao, 2001) and contributes 75 per cent of the national food grain production (Yadav, 1996). In India as well as in Himachal Pradesh, these two crops are again major food grain crops. On all India basis, total area under rice and wheat is 44.28 and 24.86 million hectares with the production of 87.00 and 72.06 million tonnes, respectively (Anonymous, 2003-04). In Himachal Pradesh, wheat occupies first position in acreage covering about 0.37 million hectare area with the production of 0.50 million tonnes, whereas in *Kharif* season the rice crop is sown on 0.08 million hectare area with the production of 0.09 million tonnes (Anonymous, 2004-05); of which about 0.08 million hectare area come under rice-wheat cropping sequence (Thakur *et al.*, 1994).

The environmental requirements for growth and development of rice and wheat crops are contrastingly different. Rice grows best under water stagnant conditions; while wheat requires a well pulverized soil with a proper balance of moisture, air and thermal regime. Rice in most parts of South and South-East Asia is traditionally cultivated in well-puddled soils. In Himachal Pradesh, rice is cultivated with wet tillage in 95 per cent of total rice area (approximately 90,000 ha). Puddling is an intensive tillage system, which brings about significant changes, especially, in physical properties of soil, including structural, hydraulic and mechanical properties. Such changes, although are favourable for rice, but not suitable for the following upland wheat crop (Sharma and De Datta, 1986; Sharma *et. al*. 2003). Consequently, wheat growth and yield are poor in post-rice soils probably constrained due to factors such as large turn around time (Fujisaka *et al.*, 1994), poor soil tilth of seedbed (Chenkual and Acharya, 1990), subsoil compaction (Bhushan and Sharma, 1997), poor drainage (Regmi *et al.*, 2002), restricting aeration (Bhushan and Sharma, 1999), nutrient stress (Hobbs, 1994) and high mechanical impedance to roots (Bhagat and Verma, 1991).

Rice-wheat is the major crop rotation of Kangra Valley of Himachal Pradesh. The average productivity of rice and wheat in Himachal Pradesh are 1.0 Mg ha^{-1} and 1.4 Mg ha^{-1} (Anonymous, 2004-05), which are far below than the national average of 2.0 Mg ha^{-1} and 2.9 Mg ha^{-1}, respectively (Anonymous, 2003-04). Wheat productivity after puddled rice is relatively low, especially in medium to fine textured soil as compared to yield after other upland cereals. Various soil physical constraints have been assigned to the relatively low wheat yields in post-rice soils in Himachal Pradesh. Puddled soils upon desiccation usually develop compact sub-surface layers having low porosity and permeability, high penetration resistance and cracks resulting in the formation of large clods upon cultivation (Sharma and Bhagat, 1993; Sharma *et al.*, 1995). Root growth in these soils may be restricted if the soil penetration resistance exceeds certain critical value. Restricted root growth may be responsible for reduction in wheat yields in post-rice soils, as a definite relationship has been shown to exist between root growth and water extraction pattern by wheat plants (Bhagat and Acharya, 1987). However, no conclusive research results are available in literature on the effect of root modification on water relations and wheat yields in post-rice soils. Therefore, the present investigation entitled, "Soil-water dynamics, root growth and wheat yield in a sequentially deep tilled post-rice soil" was conducted with the following broad objectives: -

I. To study the effect of depth of tillage on root growth of wheat in post-rice soil.

II. To study the effect of depth of tillage on soil and plant-water relations.

III. To study the effect of depth and frequency of tillage on root growth pattern of wheat *vis-a-vis* wheat yield.

REVIEW OF LITERATURE

CHAPTER-II

REVIEW OF LITERAURE

Tillage is defined as the soil related actions necessary for better crop production (Bonne, 1988). It is an integral part of cropping system aimed at optimizing crop production by solving specific soil related ecological constraints to crop production. There are several specific reasons for soil tillage. Short term reason include optimization of soil temperature and moisture regimes, seed germination, emergence and seedling establishment, root proliferation and development, minimizing weed competition and energy input. Long term reasons are maintenance of soil productivity and sustainable management of soil and water resources (Prihar *et al.*, 2000).

Soil tillage systems such as conventional, reduced and deep tillage are considered as important soil management practices. These practices alter the soil physical environment and affect the plant and root growth, thereby, water and nutrient uptake and crop yields. The effect of tillage on moisture conservation depends upon soil type and climatic conditions (Prihar *et al.*, 1968), time of tillage (Gill *et al.*, 1977), porosity and thickness of mulch created by tillage (Acharya and Prihar, 1969) and size of aggregates or clods left at the surface after tillage (Chaudhary and Acharya, 1993). Therefore the literature relevant to the proposed investigation entitled, "Soil-water dynamics, root growth and wheat yield in a sequentially deep tilled post-rice soil" has been briefly reviewed and documented in this chapter under the following heads: -

2.1 Physical characteristics of post-rice soils

Puddling refers to a tillage system in which soil is repeatedly ploughed and harrowed under submerged conditions to make the soil soft for transplanting and less permeable to water. It is an intensive tillage system. Puddling breaks the soil aggregates and peds into fine plastic mud, thereby practically eliminating the water transmission (macro) pores (Bodman and Rubin, 1984; Sharma and De Datta, 1986; Acharya and Sood, 1992). Dispersed clay particles settle in horizontal orientation in the puddle layer. Fine clay particles move downwards with percolation water, and clog the remaining macro-pores (Adachi, 1990). This results in drastic reduction in percolation losses of water and nutrients (Sharma and De Datta, 1985; Sharma *et al.*, 1988). Depth of puddling plays a significant role in reducing percolation losses. Sharma and Bhagat (1993) reported exponential reduction in water flux through soils with increase in puddling depth.

Puddled soils shrink on drying, become compact and hard, and produce surface fissures varying in size, depth and pattern (Bolton and De Datta, 1979; Sur *et al.*, 1981; Bhagat and Acharya, 1987; Prihar *et al.*, 1990). Sharma *et al.* (1995) observed the development of wide and deep cracks in a hexagonal pattern upon drying of puddle silty clay loam soil after rice harvest. The total length of the cracks of width <5, 5 to 10, 10 to 15, and 15 to 20 mm was 0.9, 2.5, 2.6 and 2.1 m m^{-2} area, respectively, with a corresponding volume of 0.2×10^{-4}, 7.0×10^{-4}, 1.8×10^{-4} and 2.5×10^{-4} m^3 m^{-2}, respectively. The cracking width was positively and linearly correlated with cracking depth. The cracking pattern of the soil surface affects the hydrodynamic properties of soil. Cracking extends the soil air interface into the soil profile, thereby increasing the moisture loss through evaporation. It also influences the extent and size distribution of clod formation during land preparation and, thus, the tilth of seed bed for wheat.

Reduction in water transmission (macro) pores resulted in a corresponding increase in water retention and residual pores. Water retention in puddle soils always exceeds that in non-puddled soils, usually below -0.01 MPa water potential. Evaporation losses from puddled soils are relatively low, and it may take weeks to months before a puddle soil reaches the optimum moisture content for tillage (Sharma and De Datta, 1986).

The draft-power requirement of dried post-rice soils is very high. Bhagat *et al.* (1994) reported 5.4 GJ ha^{-1} energy requirements for plowing a silty clay loam soil after rice harvest. Further, puddling, decreases the soil moisture range over which an optimum soil tilth can be obtained for sowing the following upland crop. According to Utomo and Dexter (1981), for some soils, gravimetric moisture content around 0.9 times the plastic limit provided the maximum friability. At this moisture content, soil tillage maximizes the proportion of small aggregates (Ojeniyi and Dexter, 1979).

The long-term effect of puddling is the formation of hardpan in subsoil below the puddle layer at 0.1-0.45 m depths (Sur *et al.*, 1981; Sharma and De Datta, 1986; Sawhney and Sehgal, 1989; Chenkual and Acharya, 1990; Rahman, 1991; Boparai *et al.*, 1992). Chenkual and Acharya (1990) observed higher bulk density throughout the 0.0-0.3 m profile under rice-wheat than under maize-wheat in silt loam, silty clay loam, and silty clay soils. Titkov and Gausev (1989) recorded in increase in bulk density from 1.27-1.29 to 1.45-1.54 Mg m^{-3}, and a decrease in porosity from 48-53 to 42-46 per cent at the 0.1-0.36 m depth in soil under rice monoculture system. According to a survey of 35 rice growing locations in South and South-East Asia, the soil horizon below the 0.1-0.15 m depth had mechanical impedance >2.8 MPa, high enough to inhibit root elongation of most crop plants (Hasegawa *et al.*, 1985).

Sub-surface hardpans may develop due to physical compaction caused by the use of heavy machinery; animal and human processes during tillage, transplanting, weeding, and other processes; and chemical precipitation of Fe, Mn, and Si in the subsoil layers. It may take as little as 3 year, as in fine sandy loam, and as many as 200 year, as in polder lands, to develop a hardpan (Sharma and De Datta, 1986).

Hardpans are characterized by high bulk density and penetration resistance, and low porosity and water permeability (Hasegawa *et al.,* 1985; Sharma and De Datta, 1985; Sharma *et al.,* 1988). In one study (Sur *et al.,* 1981), the saturated hydraulic conductivity (K_s) of a 0.15-0.2 m layer under rice-wheat rotation was less than one-half (1.14 cm ha^{-1}) that under maize-wheat rotation (2.58 cm hr^{-1}). Sawhney and Sehgal (1989) observed lower cumulative water intake under rice-wheat than under maize-wheat rotation due to the presence of a compact layer at the 0.12-0.45 m depth. Meelu *et al.* (1979) observed 1.86 cm hr^{-1} infiltrability of soil under maize-wheat-mungbean rotation compared with 2.76 cm hr^{-1} in soil under maize-wheat-mungbean rotation. The low infiltrability in the former case was attributed to the subsoil compaction. Yun-Sheng (1983) observed a decline in percolation rate from 0.360-4.212 to 0.072-0.432 cm hr^{-1} due to a shift in cropping system from rice-wheat to rice-rice-wheat. The 'K_s' of the plow layer was as high as 43.2 cm hr^{-1}, compared with 0.07 cm hr^{-1} in the plow pan; it was 0.13 cm hr^{-1} in soil below the plow pan. Thus, the 'K_s' value of the plow pan was about 0.15 per cent of that in the plow layer. Chenkual and Acharya (1990) also observed lower infiltrability due to high bulk density under rice-wheat than under maize-wheat system.

2.2 Constraints in releazing optimum post-rice wheat yields

Wheat, in general, requires a well-drained soil with good aeration for producing potential yield. Poor soil aeration is the single most important soil constraint responsible for low wheat yields after wetland rice, especially in medium to fine textured soils (Bhushan and Sharma, 1999). The significance of soil physical properties on wheat yield, however, may be seen probably at relatively higher production levels. In a long-term field experiment, improvement in soil physical properties contributed only <20 per cent toward increased wheat yields at yield levels >3 Mg ha^{-1}, the rest of the yield increase came from improved nutrient status of the soil (Sharma and Verma, 2001; Sharad and Verma, 2001; Bhushan and Sharma, unpublished data). Other factors, which are the indirect consequence of puddling, are responsible for reduced wheat yields in post-rice soils. Different factors that adversely affect wheat yields in post-rice soils are described below: -

2.2.1 Poor soil tilth

Medium (dominating in clay fraction) to fine-textured soils are difficult to till after rice harvest because of their massive structure, high bulk density, and high draft-power requirement. Sometimes the draft-power requirement is so high that it becomes difficult to till them with the animal-drawn countryside plow or even small tractors. Upon tillage, they break into medium to large clods, having a high breaking strength (Sharma and Bhagat, 1993). To crush these clods into a fine tilth is a time and energy intensive process. In spite of the energy and time spent on crushing, the mean weight diameter of soil aggregates of the seed bed, most of the time, remain large, resulting in poor seed-soil contact. Larger clods also permit greater water losses from the surface layer and may cause seed-zone moisture to fall below the level needed for seed germination (Prihar *et al.,* 1985). The large clods cause poor germination and seedling emergence, resulting in unsatisfactory crop stand of wheat (Sawhney and Sehgal, 1989; Chenkual and Acharya, 1990; Hobbs, 1994). Therefore, cloddy soil tilth is unfavourable for the wheat crop.

2.2.2 Subsoil compaction

Sub-surface compaction is beneficial for rice, as it lowers percolation losses and increases water and nutrient use efficiency. However, its effect on wheat yield is determined by the penetration resistance and water permeability of the compact layer. Some degree of. sub-surface compaction in coarse-textured soils (below the critical value that restricts root growth) may favor wheat yields by decreasing leaching losses of water and nutrients, especially N. If sub-surface compaction is so high that it restricts the root growth, then to achieve the same wheat yield precise regulation of water and nutrients is a must in soil above the compact layer (Bhushan and Sharma, 1997). Otherwise, a crop with restricted root growth may experience nutritional stress and produce lower yield. Occasional or permanent water-logging in soils with sub-surface compaction may cause oxygen stress, decrease soil redox potential, and favor accumulation of phytotoxins in the root-zone. It lowers wheat yields. Under such circumstances, precise regulation of soil moisture through improvement in soil drainage properties is needed to improve wheat yields. Soil penetration resistance in a given soil is influenced by the bulk density, pore-size distribution, rigidity of pore system, and soil moisture content. Sharma *et al.*

(1971) observed a decline in root mass of wheat in a clay soil above a bulk density of 1.42 Mg m^{-3} in the surface layer and 1.55 Mg m^{-3} in the sub-surface layer. Root mass in the sub-surface layer was the same at bulk densities from 1.10 to 1.42 Mg m^{-3}. They concluded that 1.20 to 1.30 Mg m^{-3} bulk density is ideal for root growth of wheat in clay soils. Tomar *et al.* (1981) observed 80 to 85 per cent of the total root mass of wheat within the top 0.1 m soil layer, with a bulk density of 1.25 Mg m^{-3}. Root growth declined when the bulk density of soil below 0.1 m depth increased from 1.45 to 1.55 Mg m^{-3}. Barraclogh and Weir (1988) reported a reduction in vertical extension of winter wheat root system in a sandy loam soil layer at the 0.35 m depth compacted to a bulk density of 1.8 Mg m^{-3}. Roots were largely confined above the pan during the early period of wheat. Around anthesis, roots reached a maximum depth of 1.0 m, compared with 1.4 m in pan-free soil. However, the total root length above the pan was the same in soil with and without a hardpan. Early shoot growth was reduced due to pan formation.

Sur *et al.* (1981) observed reduced root growth of wheat below a 0.15-0.2 m depth after rice than after a maize crop in a sandy loam soil. Total root mass within 0.9-1.8 m profile was 48 per cent higher after maize than after rice. Restricted root growth of wheat after rice than after maize was also observed by other workers (Prihar *et al.,* 1975; Chenkual and Acharya, 1990; Boparai *et al.,* 1992). Restricted root growth may result into restricted nutrient uptake and low crop yields. Barraclough and Weir (1988) obtained a 5 per cent lower grain yield in winter wheat in a soil with a pan at the 0.35 m depth than in the pan-free soil. Rao and Kathavate (1972) observed a decline in wheat yield when the 0.075-0.3 m soil layer was compacted to 1.5 Mg m^{-3} bulk density.

Water-logging adversely affects growth and yield of wheat due to depletion of dissolved oxygen, accumulation of toxins, and/or changes in concentrations of nutrient ions in soil solution (Trought and Drew, 1980). Bhushan and Sharma (1999) concluded that poor soil aeration was the most limiting factor for wheat yield in post-rice soils. Wheat is sensitive to water-logging, particularly during early growth periods (Hobbs, 1994); it decreases with age and duration of water-logging (Belford, 1981; Belford *et al.*, 1984; Cannell *et al.*, 1984; Meyer and Barrs, 1988). In one study, very few wheat plants survived more than 6 days of water-logging during germination and emergence stage. After emergence, water-logging reduced tillering (Belford *et al.*, 1984). Wheat plants under excess water conditions turn yellow, and show reduced tillering (Hobbs, 1994), shoot biomass (Guyot and Prioul, 1985), leaf number on the main stem (Cai and Cao, 1987), and apparent photosynthesis (Meyer and Barrs, 1988).

It is generally agreed that the aeration porosity of soil for the successful cultivation of upland crops must be more than 10 per cent. Proper drainage in water-logged soils, therefore, must be provided to keep a proper balance of air and water in the rhizosphere.

2.2.3 Large turnaround time

Puddled soils have relatively high water retention because of increased micro-porosity (Taylor, 1972; Sharma and De Datta, 1986). Relatively more energy is required to evaporate the same quantity of water in puddle than in un-puddled soils, while the atmospheric evaporativity after rice harvest is relatively low. In addition, higher unsaturated hydraulic conductivity of puddle soils may also help keep the surface soil wet longer by transporting more water upward to the soil surface from the lower profile (Sharma and De Datta, 1986). As a result, puddled soils remain more wet than un-puddled soils for a longer time (Sharma *et al.*, 1988). The situation is aggravated further if a shallow water table exists that is capable of keeping the soil surface wet through capillarity. In many low-lying areas, therefore, it takes several weeks before poorly drained puddle soils reach a state with workable moisture content.

Longer turnaround time delays wheat planting, which results in low yields. Delayed planting has been identified as one of the serious causes of low wheat productivity in rice-wheat areas of South Asia (Fujisaka *et al.*, 1994). According to an estimate, each day of delay in planting after 18 November lowered wheat yield by 0.04 Mg ha^{-1} (Regmi *et al.*, 2002). Hobbs *et al.* (1996) reported a yield decline of 1 per cent (equivalent to 0.035 Mg ha^{-1} d^{-1}) for each day of delay in wheat planting beyond the optimum sowing date (15-20 November). According to Aggarwal *et al.* (2000), potential wheat yields in the IGP (except West Bengal) under late sown conditions were lower than in optimal sown conditions by almost 0.6-1.5 Mg ha^{-1}. In West Bengal, no reduction in potential wheat yield was apparent. These data emphasize that timely sowing of wheat is crucial for maximizing wheat yields in post-rice soils. Data from various farmers' participatory trials in the IGP have also shown that wheat yields may be increased in rice soils by enhancing the date of planting of wheat.

2.3 Effect of depth of tillage on soil physical properties of wheat crop

The physical properties (mechanical behaviour) of a soil greatly influence its use and behaviour towards plant growth. The plant support, root penetration, drainage, aeration, retention of moisture, and plant nutrients are linked with the physical properties of soil. Physical properties also influence the chemical and biological behaviour of all soils. Soil compaction changes the soil physical parameters and water infiltration that cause reduction in the crop yield. Proper sub-soiling or deep tillage alleviates the negative effect of soil compaction and make the soil favorable for optimum crop production (Akinci, 2004).

2.3.1 Soil water content

Tillage affects the soil water status as well as capacity of plants to utilize it. It increases the detention of surface water and its entry (infiltration) into the soil. Moreover, it also influences the soil wetness through reduction in evaporation and weed control. Tillage not only conserves the moisture in the profile but also helps in carrying over the moisture in the seed-zone. Several workers have reported that deep ploughing increases soil water storage and crop yields (Carlson, 1978; Unger, 1979; Bhagat and Acharya, 1987; Sharma and Acharya, 1993).

Gupta (1987) indicated that all tillage conditions (no disking, one disking or three disking) increased the moisture retention by 8 to 20 per cent in wheat grown field. Khan and Raja (1989) reported higher soil moisture with tillage depth of 0.2 m compared to 0.1 m depth. Campbell and Akhtar (1990) reported greater soil moisture recharge during heavy rainfall with deep tillage in fallow-wheat sequence compared to conventional tillage.

Carefoot (1990) reported that soil water content in the top 0.075 m soil layer was greater in no tillage than in conventional tillage treatment during the growing seasons of winter wheat-barley-fallow system in a clay loam soil. Sharma (1991) showed lowest profile moisture storage in sandy loam soil at Faizabad and its utilization in minimum tillage compare to reduced or conventional tillage. Lawerence *et al.* (1994) reported greater soil water content in the 1.0-1.8 m soil layer in zero tilled wheat plots than conventional tilled wheat in medium-textured soils under rainfed conditions.

Allen *et al.* (1995) was conducted a field experiment in the Southern High Plains of the USA on a clay loam soil and reported that the 1986 deep tillage increased deep soil water storage between the 1.0 and 2.3 m depths during 1988 to 1992. Water use efficiencies were 8 per cent greater for the deep ploughing treatments. Further, they observed irrigation intake increased 40 per cent (52 mm) of soil water content with 0.6 m deep ploughing; however, there was no additional increase for 0.8 m ploughing. Similarly, Pikul (1999) found that average water content of the top 1.2 m of sandy loam soil in the spring year was 21 mm greater on sub-soiled plot than on not sub-soiled plot.

2.3.2 Bulk density

Bulk density is a widely used soil parameter to know the structure status of the soils. The magnitude of change in bulk density of soil depends upon its antecedent properties, time of measurement, depth and intensity of tillage operations. Soil loosening decreases and compaction increases the bulk density. The deep tillage of a sandy soil decreases the bulk density of tilled zone more than that is achieved by conventional tillage (Gajri *et al.*, 1997). No tillage generally increases the bulk density of soil in surface layers. Unlike tillage, the compaction of a sandy soil increases the bulk density of surface layer.

Yozar (1985) found higher soil bulk densities in minimum tillage plots as compared to conventional tillage. Similarly, Gupta (1987) indicated that all tillage conditions (no disking, one disking or three disking) in wheat crop decreases the bulk density by 0.05 to 0.07 g cm^{-3} and soil strength by 1.25 to 3.25 kg cm^{-1}.

Pelegrin *et al.* (1990) reported higher bulk density under zero tilled wheat in sandy loam soils compared with conventional tilled plots. Hollaway and Dexter (1991) noticed that bulk density in South Australia was reduced by deeper tillage and increased by re-compaction, but densities were generally not excessive, despite high penetration resistance. Similarly, Rahman (1991) while comparing four tillage treatments on a gray flood plain soil of Bangladesh reported that irrigation and normal tillage had little influence on the bulk density as compared to deep tillage. Khakural *et al.* (1992) in USA showed that no tillage treatment had higher bulk density than the mouldboard ploughing treatment in well drained and fine loamy soil.

It is generally recognized that there is a need for both primary as well as secondary tillage operations for land preparation before wheat sowing. Aggarwal *et al.* (1992) observed that chiseling after a primary tillage in wheat field lowered the bulk density by loosening the soil to greater depths and created favourable environment for better root growth and proliferation. Gajri *et al.* (1997) reported that deep tillage on alluvial sand in north-west India also decreased bulk density and soil strength in soil tilled zone and increased the depth and density of rooting while frequent small irrigation enhanced root growth during the dry years.

Bordovsky (1999) was conducted a field experiment in Texas, USA on a fine sandy loam soil and found that bulk density of wheat grown field under the reduced tillage system was higher than with the conventional tillage system. Because of higher bulk density, use of a reduced tillage system may result in the need for occasional deep chiseling to reduce the effects of compaction.

2.3.3 Soil penetration resistance

The soil strength increases with increase in bulk density and decreases with increase in soil water content. Conservation tillage usually increases the soil strength in surface layers. Loosening of soil by tillage also decreases cohesiveness and particle to particle contact and hence reduces soil strength in the tilled layer. Soil penetration resistance was generally influenced by different tillage methods (no tillage, conventional tillage and deep tillage). Greater we tilled the soil at different depths, less the soil penetration resistance values and vice-versa (Hollaway and Dexter, 1991). Pelegrin *et al.*

(1990) reported higher soil penetration resistance in zero tilled plots of wheat as compared with conventional tilled plots. Pikul (1999) reported that the cone index of the top sandy loam 0.3 m of wheat soil in eastern Montana 2.5 years after sub-soiling was lower on sub-soiled plot (891 kPa) compared with not sub-soiled plot (981 kPa).

Busscher *et al.* (2000) indicated that disced, non-deep-tilled treatments resulted in a pan at the 0.2-0.3 m depth. In deep-tilled treatments in wheat field, mean profile cone indices on loamy soil were 0.31 to 0.36 MPa lower than treatments not deep tilled. Ishaq *et al.* (2002) found that soil penetration resistance on a sandy clay loam soil in wheat crop was lower for deep tillage (DT) than conventional tillage (CT) and minimum tillage (MT). Similarly, Abu Hamdeh (2003) reported that soil cone index was still affected from 0.1 down to 0.5 m by axle load in Jordan.

2.3.4 Infiltration

Infiltration is one of the most important processes in the soil phase of the hydrological cycle because its rate often determines the amount of run-off over the soil surface during rainstorms. Tillage can modify soil surface conditions to retain water for longer time to promote greater infiltration in soils that are slowly permeable (Burwell *et al.*, 1966). Gupta (1987) showed that all tillage conditions (no disking, one disking or three disking) in wheat soil increased the infiltration rate by 10 to 20 per cent. Aggarwal *et al.* (1992) observed that deep tillage significantly increased the infiltration rate of a silt loam soil of wheat crop in the Doon Valley, India. Further, Aggarwal *et al.* (1997) also observed that deep tilled systems increased infiltration rates of a clay loam soil in wheat crop than, that under the minimum tillage system. Pikul (1999) found that final water infiltration rate averaged 15 mm hr^{-1} on sub-soiled plot (PT) and 6 mm hr^{-1} on not sub-soiled plot (NOPT) for nine months after sub-soiling.

Abu Hamdeh (2003) reported that infiltration rate was strongly affected by the compaction and increased with deep tillage at four depths (0.1-0.5 m) in wheat crop. Further, Barzegar *et al.* (2004), while working on silty clay loam soil in Southwestern Iran noticed that greater infiltration rate was found in conventional tillage (11.7 to 13.0 mm hr^{-1}) for wheat crop than either reduced tillage (7.0 to 9.1 mm hr^{-1}) or no tillage (7.0 to 9.0 mm hr^{-1}). Soil loosening in the conventional tillage probably contributed to the increased infiltration rate.

2.3.5 Hydraulic conductivity

Hydraulic conductivity, as the name suggests, measures the ability of the soil to conduct water and is expressed as length per unit time. In other words, it is the ratio of the flux to the hydraulic gradient. Generally, the hydraulic conductivity depends on both the nature of the soil (the porous matrix) and the fluid (water) properties. Coarse-textured soils having a high porosity have high hydraulic conductivity than heavy clays which have finer pores. The lower conductivity of soils having finer pores may be due to the drag exerted by the walls of the channels on the viscous fluid. In general, the hydraulic conductivity of light to heavy-textured soils may range from 10^{-2}-10^{-7} cm s^{-1}. The different tillage system increased the hydraulic conductivity as compared to no-till system which is associated with loosening of the soil (Unger and Cassel, 1991).

Chang (1992) observed that the hydraulic conductivity of zero tillage soil under wheat crop was less than that of conventional tillage soil in the tillage zone and greater below the tillage zone. Aggarwal *et al.* (1992) observed that chiseling after a primary tillage in a wheat crop increased saturated hydraulic conductivity. Further, Aggarwal *et al.* (1997) observed that deep tilled systems increased hydraulic conductivity of surface and sub-surface soil of wheat crop than, that under the minimum tillage system. Bordovsky (1999) was conducted a field experiment in Texas, USA on a fine sandy loam soil and found that saturated hydraulic conductivity of the surface soil was increased by reduced tillage practices compared with conventional tillage. This may have been attributing to higher amounts of micro-aggregates and larger macro-pores under the reduced tillage system.

Ferreras (2000) noticed that the saturated hydraulic conductivity of wheat crop grown on loam soil was significantly lower in no tillage (3.5×10^{-7} m s^{-1}) than in conventional tillage plots (10.9×10^{-7} m s^{-1}).

2.4 Effect of depth of tillage on wheat root growth

Root growth means lengthening of a root due to elongation of new cells that are formed in the apical region, which push root tip through the surrounding medium. In general, more than 90 per cent of the total root mass (dry) is found in the top 0.3 m soil layer. The access of crop to water and nutrients is directly related to the size of its root system. Tillage affects the depth and density of rooting by modifying the mechanical impedance, continuity, stability and size distribution of pores, air water dynamics and thermal regimes of the soil (Prihar *et al.*, 2000). The role of tillage is to make rootable spaces within the soil by reducing the soil strength and increasing the macro-porosity. Loosening of root-restricting hard soil layers by tillage promotes root growth into deeper soil layers. The effect of tillage on root growth is governed by soil type, climate and other management practices. Deep tillage (sub-soiling to 0.4 m depth) has been found to increase the depth and density of corn roots (Arora *et al.*, 1991). However, tillage effect on root growth is more pronounced on sand followed by loamy sand and sandy loam soils.

The rate of water uptake from a given volume of soil depends upon rooting density, the hydraulic conductivity of soil and the differences between the average soil water suction (Gardner, 1964). The water uptake is highest where the rooting density is the greatest, provided that the matric suction is uniform throughout all depths of the rooting zone. Normally, there are differences in the rooting density within the soil profile which result in the non-uniformity of water uptake from different soil profile depths (Ogata *et al.*, 1960). In general, rooting density is greatest in the upper layers than in the lower layers of the rooting zone and the roots deep with in the profile are less effective than those near the soil surface (Klepper *et al.*, 1973). The water content in the lower layers is thus depleted by two simultaneous processes viz., uptake by the roots of that layer, and the flux divergence, the direction of which would depend upon the direction of the suction gradients. Ehrler *et al.* (1980) indicated that the water uptake by oats was functionally related to rooting density and soil water potential.

Tillage helps in controlling weeds, improvement in soil physical properties, free exchange of gases in soil and air which results in better root growth, their penetration to sub-surface depth and hence greater utilization of subsoil moisture (Orellana *et al.*, 1990). Several workers have reported that deep tillage increases soil water storage enhances root proliferation of deeply stored water and crop yields (Acharya and Bhagat, 1984; Bhagat and Acharya, 1987; Sharma and Acharya, 1993; Thompson, 2001). Similarly, Bennie and Botha (1985) observed that deep ploughing in wheat resulted in higher rooting density in the deeper soil layers and rate of water extraction and evapotranspiration throughout the growing season.

The subsoil pans have mechanical strengths that restrict root growth (Busscher *et al.*, 2000). To reduce strengths, soils are deep tilled annually and perhaps biannually for double cropping in the United States (Unger and Jones, 1998). This practice is followed in the United States because depth of tillage has a significant interaction on root growth and crop yields. Busscher *et al.* (2000) reported that root growth of wheat increased significantly as mean or maximum soil strength decreased. Bhagat and Acharya (1988) reported that deep tillage maintained higher water withdrawal rate from the sub-surface depths. The total water withdrawal rate from the profile (0.0-0.6 m depth) was the highest (1.83 cm d^{-1}) under deep tillage and the lowest (0.574 cm d^{-1}) under zero tillage in wheat. Werner (1988) obtained increased uptake of water by 20-40 mm in 0.0-1.0 m soil layer by deep loosening of soil in wheat crop.

Campbell and Akhtar (1990) found that deep tillage increased wheat yield by decreasing soil strength and allowing greeter and deeper root development. Sharma and Acharya (1993) reported higher root water uptake under deep ploughing (0.0-0.3 m) as compared to conventional tillage (0.0-0.15 m). Similarly, Hall *et al.* (1994) observed increased water storage and depletion with deep tillage. Allen *et al.* (1995) while working on Pullman clay loam in the Southern high plains of USA also observed that slowly permeable soils respond to deep tillage with increased water intake.

Continuous practice of lowland rice based cropping sequence in general results in the formation of hard pans. Hollaway and Dexter (1991) reported that in South Australia, soil strength was reduced by tillage to 0.3 m, but tillage to 0.15 m did not remove a hard pan below normal tillage depth. Deep tillage resulted in enhancement of root growth and water extraction. Early post-sowing irrigation and deep tillage have been shown to reduce soil strength, stimulate crown root development and increase the rate of root extension of wheat particularly in the less retentive soils (Gajri *et al.* 1991). These studies further indicated that irrigation and deep tillage increased root length, modified density profiles, reduced water depletion and increased grain yields. Aggarwal *et al.* (1992) also observed that wheat root length density in the 0.0-0.25 m soil layer was 3-6 times greater with deep tillage than with shallow minimum and normal tillage. Sharma and Acharya (1993) reported higher root water uptake under deep ploughing (0.0-0.3 m) as compared to conventional tillage.

In a long term study in Taiwan, Zhao *et al.* (1997) observed that disc ploughing in autumn before the sowing of wheat promoted root growth for the first 1-2 years of the rotation. After 3-4 years, a pan formed under the discing layer (0.15-0.2 m) which impeded root growth into deeper soil layers and accelerated root senescence after flowering. The study suggested that a system in which disc ploughing was alternated with mouldboard ploughing or deep chiseling could promote wheat root growth and increase crop yield.

Khan *et al.* (1998) reported research results of field experiments conducted at two locations in Bangladesh i.e. silty clay loam soil of Joydebpur and clay loam soil of Jessore, which indicated that root weight density was always maximum in the surface layers in all treatments (minimum tillage, conventional tillage and deep tillage). A considerable root growth was noticed below 0.3 m depth in deep tilled plots and lower root weight density was found in minimum tilled plots. Use of continuous deep tillage on alternate systems prevented the formation of a dense layer in the soil profile thus facilitating the wheat roots to penetrate to lower soil depths in post-rice soils. Bhushan and Sharma (1999) observed that the wheat root mass density (RMD) on clay loam soil increased progressively and significantly with the increase in root-zone depth from 0.05 to 0.3 m. In shallower root zone, probably nutritional and space constraints were responsible for reduced root growth.

Ferreras (2000) noticed that increased soil mechanical resistance under no tillage can decrease growth of wheat roots in Argentina on a loam soil and reduce dry matter accumulation and wheat yield as compared to conventional and deep tillage. Further, Hajabbasi (2001) found that tillage systems influence soil physical characteristics which in turn may alter, root characteristics, growth, and development. The upper layer (0.0-0.1 m) contained a higher quantity of root mass density (RMD), root length density (RLD) and surface area density (RSD), but the reverse was observed for the lower layer (0.3-0.4 m). The upper layer (0.0-0.1 m) contained almost 46 per cent of the total RMD, while the second (0.1-0.2 m), the third (0.2-0.3 m) and fourth (0.3-0.4 m) depths contained 23, 18.5 and 12.5 per cent of the total RMD, respectively. The average RLD of four depths for mouldboard ploughing + discing (MD), chisel ploughing + disc (CD), chisel ploughing + rotary tilling (CR) and chisel ploughing (twice) + discing (2CD) were significantly higher than ploughing with a khishchi (a regional rigid cultivator) (KD), till planting with cultivator combined drill (TP) and no tillage (NT) systems (24.9, 25.1, 24.2, and 23.8, as compared with 22.3, 21.8 and 21.6 km m^{-3}, respectively). Results of this study showed that, for the arid soils of central Iran, with weak structure and low organic matter content, as the number of tillage operations increased, root morphological characteristics improved.

Ishaq *et al.* (2003) studied the effect of tillage on wheat crop in Punjab (Pakistan) on a sandy clay loam soil and reported that almost 50 per cent more root length density was measured at 0.0-0.15 m than at 0.15-0.30 m soil depths. Similarly, Xi Ying *et al.* (2004) reported that winter wheat in the North China Plain had a prolific root system with an average maximum rooting depth of 2 m. Most of the root system was concentrated in the upper 0.4 m of soil. Root length density in the top layer of soil (0.0-0.2 m) was very high, with values more than 5 cm cm^{-3}. The distribution of water uptake from the soil profile under high soil moisture conditions was the same as the distribution of root length density. The roots in the top layer of soil played an important role in soil water uptake. When root length density was less than 0.8 cm cm^{-3}, the root was the main factor limiting the complete utilization of soil water by crops. The scarcity of roots in the deep soil layers restricted the full utilization of soil water by the crops. Results showed that deep tillage to break the soil pan improved root growth in the deeper soil layers, and sowing the crop evenly also enhanced water uptake from the top soil layer to compete with soil evaporation.

2.5 Effect of depth of tillage on wheat yield

For a tillage system to have a positive effect on growth and yields of crops, it must alleviate soil constraints which limit the yield. The crop performance under different tillage systems depend upon the site-specific soil and climate constraints and allied management practices (irrigation, fertilizer management, weed control and residue status). Deep tillage of coarse-textured soils, exhibiting increase in soil strength on drying, with a chisel which disrupts the soil to a depth of 0.4 m without inversion, has been found to increase the yield of maize, wheat, mustard and sunflower. The magnitude of yield increase is more in summer season than in winter season. Also, the yield increase varies with soil water retentivity. It is more on sand and loamy soil than on sandy loam soils. In loose sands, compaction of soils increases micro-porosity and consequently there is an increase in water and nutrient retention leading to an increase in the yield of crops, as has been observed in pearl-millets and other crops (Majumdar, 1994). Depending upon the depth and density of sub-surface layer, sub-soiling with chisel to 0.4 m depth or profile modification increases the infiltration of water and storage in the profile by breaking the restricting the layer. The tillage practices also encourage deeper rooting and hence better mining of water by the crops, resulting in high yields (Sharma and Acharya, 1993; Ishaq *et al.*, 2003).

Pot and Ouwerkerk (1980) reported that grain and straw yields with minimum tillage were 9 and 12 per cent lower, respectively than conventional tillage. Gajri *et al.* (1991), while working on wheat (cv. HD-2329) crop grown in 3 years at Ludhiana on loamy sand and sandy loam soils reported that mean grain yield was higher with deep tillage (5.0 Mg ha^{-1}) as compared to conventional tillage (4.6 Mg ha^{-1}). It also concluded that soil related constraints on root growth may be alleviated by deep tillage, which corresponds to higher wheat yield. Sharma and Kharwara (1994) observed that grain yield of irrigated as well as rainfed wheat was the same with minimum and conventional tillage, but was lowest with no tillage. Shafiq *et al.* (1994) reported that grain yield of rainfed wheat from zero, conventional and deep tilled un-weeded plots were 1.71, 2.26 and 2.71 Mg ha^{-1}, respectively compared with 2.31, 2.54 and 2.97 Mg ha^{-1} where herbicide were applied. Allen *et al.* (1995) indicated that wheat grain yields increased from 4.2 to 5.0 Mg ha^{-1} (19%) for the 0.4 m or deeper ploughing.

Singh and Singh (1996) showed the maximum wheat yield from one harrowing during first year while in the second year conventionally tilled plots yielded highest. Gajri *et al.* (1997) reported that an optimum combination, in terms of crop yields was obtained by combining deep tillage (Sub-soiling to 0.4-0.45 m) with frequent low volume irrigation in which an increase of 2.3 Mg ha^{-1} was achieved. Deep tilled systems yielded more wheat crop than, that under the minimum tillage system (Bhagat and Chand, 1994; Aggarwal *et al.*, 1997). Singh *et al.* (1998) observed 15 to 25 per cent higher wheat yields with conventional tillage than zero tillage in medium-textured soils. The lower wheat yield in zero tillage plots was associated with heavy crop-weed competition. Moreover, the population of monocot weeds was significantly higher in zero than in conventional tillage plots.

Bajpai and Tripathi (2000) noticed that conventional tillage of wheat produced significantly higher (25%) grain yield than that of zero tillage in silty clay loam soil of Uttar Pradesh, India. In a field study in the Southern Coastal Plains of the USA, Busscher *et al.* (2000) found that for every MPa decrease in mean profile cone index due to tillage (0.0-0.3 m), wheat yields increased from 1.5 to 1.7 Mg ha^{-1} on loamy sand.

Abu Hamdeh (2003) indicated that in Jordan, deep tillage upto 0.1 to 0.5 m of the compacted plots removed the compaction effect and improved wheat yields in all treatments. Similarly, Tomar (2003) reported that significantly higher grain yield of wheat (cv. HD-2285) on alluvial sandy loam well drained soils at Modipuram, Uttar Pradesh was recorded with summer deep tillage and conventional tillage in direct seeded rice followed by conventional tillage in succeeding wheat (4.59 Mg ha^{-1}) compared with zero tillage (4.11 Mg ha^{-1}). Maximum grain yield (4.72 Mg ha^{-1}) was obtained with two hand weedings, which was significantly higher than herbicides alone (4.07 Mg ha^{-1}).

MATERIAL AND METHODS

CHAPTER-III

MATERIAL AND METHODS

The present investigation entitled, "Soil-water dynamics, root growth and wheat yield in a sequentially deep tilled post-rice soil" was carried out during *Rabi* season, 2002-04 and 2003-04, at the experimental farm of CSK Himachal Pradesh Krishi Vishvavidyalaya, Palampur (Himachal Pradesh), India. The details of the material and the methods used in carrying out the experimental work are presented in this chapter under the following heads: -

3.1 General description of the study area
    3.1.1 Location
    3.1.2 Climate and weather
    3.1.3 Soils
3.2 Experimental background
3.3 Treatment details
3.4 Experimental layout
3.5 Soil studies
    3.5.1 Structural properties
        3.5.1.1 Particle size distribution
        3.5.1.2 Bulk density
        3.5.1.3 Particle density
        3.5.1.4 Total porosity
        3.5.1.5 Soil penetration resistance

- 3.5.2 Hydraulic properties
    - 3.5.2.1 Soil water content
    - 3.5.2.2 Soil water retention
    - 3.5.2.3 Hydraulic conductivity
        - 3.5.2.3.1 Saturated hydraulic conductivity
        - 3.5.2.3.2 Unsaturated hydraulic conductivity
    - 3.5.2.4 Soil matric potential
    - 3.5.2.5 Infiltration characteristics
- 3.5.3 Mechanical properties
    - 3.5.3.1 Energy required for land preparation
- 3.5.4 Soil temperature
- 3.5.5 Soil chemical and physico-chemical properties
    - 3.5.5.1 Soil pH
    - 3.5.5.2 Organic carbon
    - 3.5.5.3 Cation exchange capacity
    - 3.5.5.4 Available nutrients
        - 3.5.5.4.1 Available nitrogen
        - 3.5.5.4.2 Available phosphorous
        - 3.5.5.4.3 Available potassium

3.6 Plant observations

- 3.6.1 Plant growth parameters
    - 3.6.1.1 Emergence count
    - 3.6.1.2 Plant height
    - 3.6.1.3 Number of tillers

3.6.1.4 Dry matter accumulation

3.6.2 Leaf water potential

3.6.3 Root studies

3.6.3.1 Root mass density

3.6.3.2 Root length density

3.6.3.3 Root volume density

3.6.3.4 Root porosity

3.6.4 Crop yield

3.7 Meteorological parameters

3.8 Statistical analysis

3.1 General description of the study area

3.1.1 Location

The experiment was conducted at the Experimental Farm of the Department of Soil Science, CSK HPKV, Palampur (H.P.). The experimental site is situated at $32^0 6'$ N latitude and $76^0 3'$ E longitude at an elevation of about 1290 m above mean sea level. The area lies in Palam Valley of Kangra district in the foothills of Dhauladhar range and represents the high rainfall mid-hill wet-temperate zone of Himachal Pradesh in north-west Himalayas.

3.1.2 Climate and weather

The climate of the area is wet temperate, characterized by severe winters and mild summers. Annual mean temperature vary from 8.2^0C in January to around 28.0^0C during the months of May-June. The average annual rainfall of the place is about 2475 mm. The monsoons set in June end and recede in mid

September. More than 80 per cent of the total annual rainfall is received during this period only. Winter rains are meager and erratic. The relative humidity in the region varies from 46 in May to 84 per cent in July/August. The soil temperature drops as low as 2^0C during the winters and frost incidences are common.

3.1.3 Soils

The soils of the region are Gray Brown Podzols as per the Genetic System of Classification. Taxonomically, these soils fall under the Order of "Alfisols" and subgroup Typic Hapluadalf (Verma, 1979). Rice-wheat and maize-wheat are the two important cropping sequences of the region. These soils owe their origin to the fluvioglacial parent material developed from rocks like slate, phyllites, quarzites, schists and gneisses.

Before the conduct of the experiment, soil samples (0.00-0.15, 0.15-0.30 and 0.30-0.45 m soil depth) from experimental site were collected randomly from six spots and composite samples were prepared, which were air-dried, ground and sieved through 2 mm sieve and then subjected to chemical and mechanical analysis to determine the native fertility status and texture.

Soil samples from experimental site were also collected randomly from 0.00-0.15, 0.15-0.30 and 0.30-0.45 m depth for six spots for the determination of various physical properties such as particle size distribution, bulk density, particle density, total porosity, saturated hydraulic conductivity, soil water retention and infiltration before conduct of the experiment.

3.2 Experimental background

The field experiments were conducted at the Experimental Farm of the Department of Soil Science, CSK HPKV, Palampur in district Kangra for a period of two consecutive years, with rice as a general crop and wheat as a test crop. The effect of the depth of tillage on water movement in soil, root water uptake, root growth (spatial and temporal) and yield of wheat crop were monitored. The experiment was conducted in both the wet (*Kharif*) and dry (*Rabi*) seasons. The details of experimental crops are as under in Table 3.1: -

Table 3.1: Details of experimental crops

Sr. No.	Parameters	Rice	Wheat
1.	Variety	RP-2421	Surbhi (HPW-89)
2.	Seed rate (kg ha^{-1})	35	100
3.	Spacing (cm)		
	I. Rows	20	20
	II. Plants	10	-
4.	Fertilizers (kg ha^{-1})		
	I. N	90	120
	II. P_20_5	40	60
	III. K_20	40	30
5.	Sowing/ Transplanting		
	I. First Crop	July 19, 2002	November 24, 2002
	II. Second Crop	July 17, 2003	November 13, 2003
6.	Harvesting		
	I. First Crop	October 28, 2002	May 10, 2003
	II. Second Crop	October 24,2003	May 5, 2004

The nursery sowing of rice (cv RP-2421) was done on June 17 during 2002 and June 15 during 2003 with seed rate @ 35 kg ha^{-1}. Transplanting was done on July 19 during 2002 and July 17 during 2003 with 2-3 seedlings per hill at a spacing of 20 cm x 10 cm. Half quantity of nitrogen with entire quantity of phosphorous and potassium was applied as basal dose and remaining half dose of nitrogen was top dressed in two equal splits each at tillering and panicle initiation stages of rice. Rice was irrigated to keep the water standing in the plots throughout the crop seasons. The rice crop was harvested on October 28 during 2003 and October 24 during 2003.

The land was ploughed manually to different depths of 10, 20 and 40 cm for sowing of wheat (cv HPW-89). Wheat was sown at 2-3 cm soil depth in furrows using seed rate @ 100 kg ha^{-1} and row spacing of 20 cm. The wheat was sown on November 24, 2002 and November 13, 2003. In wheat crop, half of the nitrogen and whole of the phosphorous and potassium was applied as basal dose and remaining half dose of nitrogen was top dressed at tillering stage. Wheat crop was irrigated regularly to ensure optimum moisture level throughout the crop season and it was irrigated four times. Crop was harvested on May 10, 2003 and May 5, 2004 (Table 3.1).

3.3 Treatment details

Two cropping cycles of rice-wheat system was conducted during 2002-2004. During both the years, rice was raised as a general crop in seven plots with recommended package of practices under puddled and transplanted condition. During *Rabi* season, different treatments of depth of tillage were imposed and wheat crop was raised. In wheat crop, following tillage treatments as presented in Table 3.2 were imposed: -

Table 3.2: Treatment details in wheat crop

Treatments	Ist year (2002 - 03)	2nd year (2003 - 04)
T_1	No tillage (T_0)	No tillage (T_0)
T_2	10 cm deep tillage (T_{10})	10 cm deep tillage (T_{10})
T_3	20 cm deep tillage (T_{20})	20 cm deep tillage (T_{20})
T_4	40 cm deep tillage (T_{40})	40 cm deep tillage (T_{40})
T_5	10 cm deep tillage (T_{10})	No tillage (T_o)
T_6	20 cm deep tillage (T_{20})	No tillage (T_o)
T_7	40 cm deep tillage (T_{40})	No tillage (T_o)

In the first year, wheat crop was planted in the seven plots in a randomized block design having plot size 11.2 m^2. Four treatments i.e. T_0, T_{10}, T_{20} and T_{40} were imposed on four plots out of seven. In the same year, treatments such as T_{10}, T_{20} and T_{40} were doubled and grown on another three plots. Then, in second year, same treatments i.e. T_0, T_{10}, T_{20} and T_{40} were continued on four plots and the remaining three plots were kept as no tillage treatment to see whether tillage at different depths is required in second year or not (Table 3.2).

3.4 Experimental layout

Treatments were allocated for wheat crop to the individual plots in each replication using random table. The field arrangement of replications and plots has been shown in Figure 3.1. The dimensional details of the layout are furnished in Table 3.3.

REPLICATION I

T_3	T_2	T_4	T_6	T_1	T_5	T_7

REPLICATION II

T_5	T_1	T_2	T_6	T_7	T_3	T_4

REPLICATION III

T_6	T_1	T_4	T_3	T_5	T_7	T_2

	First year wheat crop season (2002- 03)	Second year wheat crop season (2003- 04)
T_1 :	No tillage (T_o)	No tillage (T_o)
T_2 :	10 cm deep tillage (T_{10})	10 cm deep tillage (T_{10})
T_3 :	20 cm deep tillage (T_{20})	20 cm deep tillage (T_{20})
T_4 :	40 cm deep tillage (T_{40})	40 cm deep tillage (T_{40})
T_5 :	10 cm deep tillage (T_{10})	No tillage (T_o)
T_6 :	20 cm deep tillage (T_{20})	No tillage (T_o)
T_7 :	40 cm deep tillage (T_{40})	No tillage (T_o)

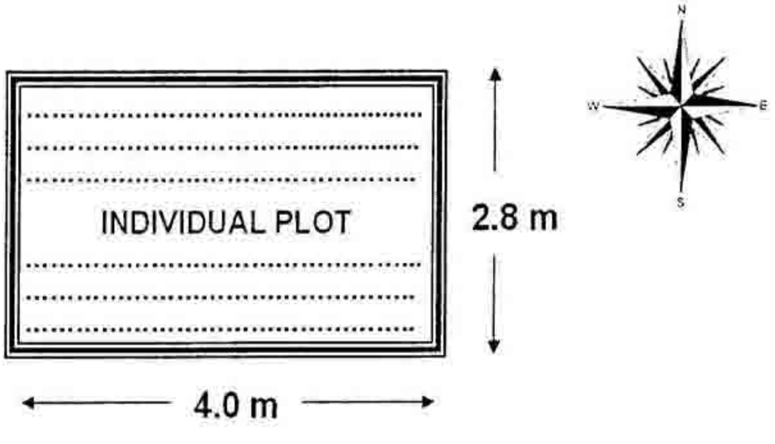


Figure 3.1: Field Layout Plan for Wheat Crop

Table 3.3: Details of layout for wheat crop

Total number of treatment combinations	:	Seven
Number of replications	:	Three
Total number of plots	:	7 x 3 = 21
Plot size (individual)	:	4m x 2.8 m = 11.2 m^2
Size of bund	:	0.20 m
Design of experiment	:	Randomized Complete Block Design

3.5 Soil studies

The soil samples were collected from three replications (seven treatments each in one replication) at the time of sowing and harvesting of crops during 2002-03 and 2003-04 for the determination of the following properties: -

3.5.1 Structural properties

3.5.1.1 Particle size distribution

The mechanical or particle size analysis of soil layers (0.00-0.15, 0.15-0.30 and 0.30-0.45 m) before the initiation of the experiment was done by the international pipette method (Piper, 1966). The textural class was determined using textural triangle given by International Society of Soil Science.

3.5.1.2 Bulk density

The bulk density of soil was determined by Core Sampler method (Singh, 1980) using metallic cores having 0.126 m length and 0.104 m internal diameter. The core had a sharp edge at the bottom to facilitate easy penetration into the soil and 0.01 m thick open circular cap fitted on the edge of the core at the top. The core was driven into the soil by hammering with a centre weight concentrated hammer. Undisturbed soil cores were collected from four different soil depths 0.0-0.1, 0.1-0.2, 0.2-0.3 and 0.3-0.4 m in triplicate. Four soil cores were removed at each depth and fresh mass of each soil core was recorded and moisture content determined by thermo-gravimetric method. The bulk density was calculated using mass-volume relationship.

$$\boxed{\rho_b = M_s / V_t}$$

Where,

ρ_b : Bulk density (Mg m^{-3})

M_S : Oven dry mass of the bulk soil (Mg)

V_t : Total volume of soil equal to the volume of metal core (m^3)

3.5.1.3. Particle density

Particle density of soil layers (0.00-0.15, 0.15-0.30 and 0.30-0.45 m) was determined by Pycnometer method (Black, 1965) using the following relationship: -

$$\boxed{\rho_s = Ms / (Mpw + Ms - Mpsw)}$$

Where,

ρ_s : Particle density (Mg m^{-3})

M_s : Mass of the soil taken (g)

M_{pw} : Mass of water filled with Pycnometer (g)

M_{psw} : Mass of Pycnometer + water + soil (g)

3.5.1.4 Total porosity

The total porosity of soil layers (0.00-0.15, 0.15-0.30 and 0.30-0.45 m) was determined before the initiation of the experiment from their bulk and particle density values, using the following relationships: -

$$\boxed{f = (1 - \rho_b/\rho_s)}$$

Where,

f : Total porosity (%)

ρ_b : Bulk density (Mg m^{-3})

ρ_s : Particle density (Mg m^{-3})

3.5.1.5 Soil penetration resistance

Soil penetration resistance refers to the resistance offered by the soil to a metal probe (representing plant roots) pushed into soil. The soil penetration resistance as a function of soil moisture content was determined after first irrigation. at flowering stage and harvesting of wheat crop. About seven observations were made per plot at each depth for computing the average soil penetration resistance, with the help of a Proctor penetrometer having 0.18 m long probe with a flat tip of 2.61 x 10^{-4} m^2 surface area.

For determining soil penetration resistance at different profile depths (0.00-0.03, 0.06-0.09, 0.12-0.15 and 0.18-0.21 m), auger holes (with tube auger) were made to the required depths. The probe of penetrometer was inserted into the hole and pushed 0.03 m into the soil.

3.5.2 Hydraulic properties

3.5.2.1 Soil water content

The weekly changes in soil water content during crop growth at different profile depths (0.0-0.1, 0.1-0.2, 0.2-0.3 and 0.3-0.4 m) were monitored by using gravimetric method before and after each rainfall. The soil water content was calculated by the following formula: -

$$\boxed{w = (M_s - M_d) / M_d \times 100}$$

Where,

w : Soil water content (%)

M_s : Fresh mass of soil sample (g)

M_d : Oven dried mass of soil sample (g)

The mass wetness was converted into volume wetness for each soil layer by multiplying mass with the bulk density of respective soil layer.

3.5.2.2 Soil water retention

Undisturbed soil core samples, drawn in metal rings (0.3 m long, 0.5 m diameter), were collected in triplicate from different depths with the help of a Core Sampler (Cat No. 200-A, manufactured by Soil Moisture Equipment Corporation, Santa Barbara, California, U.S.A).

Moisture content at 0, 33.3 and 1500 kPa suction was determined with the help of Pressure Plate Apparatus. Soil samples were saturated for 24 hours on the porous plate and then equilibrated against applied pressure. The water content was determined gravimetrically and converted into volumetric water content (θ).

The Plant available water capacity was determined from the corresponding soil water retention values, which were computed as follows: -

$$\boxed{\mathbf{PAWC = FC - PWP}}$$

Where,

PAWC : Plant available water capacity

FC : Field capacity i.e. moisture retained at 33.3 kPa suction

PWP : Permanent wilting point i.e. moisture retained at 1500 kPa suction.

3.5.2.3 Hydraulic conductivity

3.5.2.3.1 Saturated hydraulic conductivity

The undisturbed soil core samples were collected from three different soil depths 0.00-0.075, 0.075-0.15 and 0.15-0.30 m in triplicate. Saturated hydraulic conductivity was determined by constant head method and was calculated by Darcy's equation (Klute, 1965) as: -

$$\boxed{\mathbf{K_S = QL/AT\ (L+H)}}$$

Where,

K_S : Saturated hydraulic conductivity ($m\ s^{-1}$)

Q : Steady state volume of outflow from entire soil samples (m^{-3})

A : Cross sectional area of soil (m^2)

T : Time (s)

L : Length of the soil column (m)

H : Hydraulic head (m)

3.5.2.3.2 Unsaturated hydraulic conductivity

The unsaturated hydraulic conductivity of different depths of soil profile of the experimental site was determined by an internally draining profile method (Hillel *et al.*, 1972). Field determinations of *in situ* hydraulic conductivity were carried out in the study area with the help of mercury manometer tensiometers were installed in duplicate at five different soil depths such as 0.1, 0.2, 0.3, 0.4 and 0.5 m depths in 4 m x 2.8 m plot (Plate 1). The successive measurements of matric potential (or its negative suction) and water content were made, after uniformly wetting the profile, in an internal drainage process over a period extending over 30 days. During the drainage period, evaporation was eliminated by means of a pine needle covered polythene sheet laid over the surface. The data obtained for soil water content and matric potential changes, during the internal drainage of the profile was analyzed for the calculation of the unsaturated hydraulic conductivity water content relation as under:

The general equation describing flow of water in a vertical soil profile is

$$\eth\theta/\eth t = (\eth/\eth Z)(K_\theta \eth H/\eth Z) \text{ ------------------------------ } \mathbf{(1)}$$

Plate 1: Experimental set up for *in situ* hydraulic conductivity determination

Where,

θ : Volumetric wetness

t : Time

Z : Vertical depth (directed negatively downward)

K : Hydraulic conductivity

H : Hydraulic potential (sum of matric and gravitational potentials)

Integrating equation 1, we get

$$\int_0^Z (\partial\theta/\partial t)dZ = K\,(\partial H/\partial Z)_Z$$

or

$$(\partial\theta/\partial t)Z = (K\,\partial H/\partial Z)_Z$$

Z is soil depth to which measurement applies. Since the soil is covered to prevent evaporation and only the internal drainage is allowed, the total water content changes per unit time (obtained by integrating between successive soil moisture profiles down to depth Z) is given by:

$$(\partial w/\partial t)_Z = K\,(\partial H/\partial Z)_Z = q$$

Where, q is the hydraulic flux (cm day^{-1}) and w is total water content of profile to depth Z i.e.

$$W = \int_0^Z \theta dZ$$

Or finally, $K_\theta = (q)/(\eth H/\eth Z)$

The data obtained for hydraulic conductivity were fitted to the equation of the type:

$$K = ae^{b\theta}$$

Where,

K : Hydraulic conductivity ($m\ s^{-1}$)

θ : Moisture content ($m^3\ m^{-3}$)

a and b : Constants

A semi-log plot of the above equation gave the values of unsaturated hydraulic conductivity in the form of unsaturated hydraulic conductivity Vs. water content relationship.

3.5.2.4 Soil matric potential

Two banks of mercury manometers type tensiometers were installed at five different soil depths (0.1, 0.2, 0.3, 0.4 and 0.5 m) in one of the replicates to monitor changes in soil water potential. Daily observations on soil water potential were taken at 0900 hours. The matric potential was calculated by using the following equation: -

$$\boxed{\Psi_m = -12.6X + Y + Z}$$

Where,

Ψ_m : Matric potential (cm)

X : Depth of mercury in the mercury container (cm)

Y : Height of mercury reservoir above ground level (cm)

Z : Depth of installed of tensiometer (cm) from soil surface to the centre of the tensiometer porous cup

3.5.2.5 Infiltration characteristics

The infiltration behaviour of the study area prior to the studies and subsequently after the harvest of each crop was studied using double ring infiltrometers installed in duplicate. The infiltrometers were installed in the field, using specially designed circular driving cap and a crossbar hammer. Care was taken to avoid formation of cracks at the soil surface while the infiltrometers were driven into soil. A polythene sheet was kept inside the ring to avoid soil dispersion while pouring the water into it, which was removed during infiltration process. Constant water head was maintained in the infiltrometers and water intake was measured as a function of time until a steady state arrived. The water intake rate (i) as well as the accumulated intake (I) were plotted on a simple scale as a function of time. These data were then fitted to the equation of the type (Kostiakov, 1932).

$$\boxed{I = at^b} \text{ -- } (2)$$

Where,

I : Accumulated intake (cm)

t : Time (hours)

a and b : Constants

Differentiating equation (2) w.r.t. "t" we get

$$dI/dt = a.b.t^{b-1} = a.b.t^{b} / t$$

$$\boxed{\mathbf{dI/dt = b.a.t^{b} / t}} \text{ -- } \mathbf{(3)}$$

Comparing equation (2) and (3), we get

$$i = dI/dt = bI/t$$

Where, dI/dt = i gives time rate change of infiltration having dimensions LT^{-1} i.e. length per time.

3.5.3 Mechanical properties

3.5.3.1 Energy required for land preparation

The plots after the harvest of rice crop were manually prepared for sowing of wheat. The time required to dig and pulverize each plot was recorded. The energy required to prepare each plot was computed by considering the energy of an adult worker equal to 1.96 MJ human hr^{-1}. Energy required in land preparation ha^{-1} (E, GJ ha^{-1}) was computed as follows: -

$$\boxed{\mathbf{E = 1.96 \times 10^{6} \times t / A}}$$

Where, t is the time (hours) required to prepare the plot having area A (m^2).

3.5.4 Soil temperature

Soil temperature measurements at 0.05 and 0.1 m depth was determined during wheat cropping seasons (2002-03 and 2003-04) using probe digital thermometer in all the tillage treatments (Garvitech, 1956).

3.5.5 Soil chemical and physico-chemical properties

3.5.5.1 Soil pH

The soil pH was determined using glass electrode pH meter using soil-water suspension in the ratio of 1: 2.5 (Jackson, 1967).

3.5.5.2 Organic carbon

Organic carbon was determined by wet digestion method of Walkley and Black's rapid titration method, as described by Walkley and Black (1934).

3.5.5.3 Cation exchange capacity

Cation exchange capacity was determined by using neutral normal ammonium acetate extraction method given by Jackson (1967).

3.5.5.4. Available nutrients

3.5.5.4.1 Available nitrogen

Available nitrogen content was determined by alkaline potassium permanganate method (Subbiah and Asija, 1956).

3.5.5.4.2 Available phosphorous

Available phosphorous was determined by employing the method for extraction with 0.5N $NaHCo_3$ at pH 8.5 given by Olsen's (Olsen *et al.*, 1954).

3.5.5.4.3 Available potassium

Available potassium was determined by using neutral normal ammonium acetate extraction method as described by Hanway and Heidal (1952).

3.6 Plant observations

3.6.1 Plant growth parameters

The observations on plant growth characters viz., emergence count, plant height, number of tillers per square meter and dry matter accumulation were recorded at periodical interval of 30 days.

3.6.1.1 Emergence count

To work out the emergence count, three observational units of one metre row length each were selected randomly from each net plot before crop emergence and number of seeds germinated were counted thoroughly till the constant number of germinated seeds was obtained. The emergence count was expressed in number of plants emerged per square metre.

3.6.1.2 Plant height

Five plants per plot were randomly selected and height of these plants from surface to the tip of the tallest part of the plant was measured at 30 days interval starting from the date of sowing until crop harvest. The average height of the five plants was calculated and expressed as mean plant height (cm).

3.6.1.3 Number of tillers

Total number of tillers was counted per metre row length at 30 days interval after one month of sowing till constant number of tillers were observed and then mean value was recorded and converted into number of tillers per square metre.

3.6.1.4 Dry matter accumulation

For dry matter accumulation, all plants from one meter row length at 30 days interval after one month of sowing till maturity was taken by clipping the plants close to the soil surface. The plant samples were taken and dried in sun and then kept in oven dried at 65$\pm$5^{0}C till a constant weight was achieved. The values thus obtained were averaged and converted into dry weight (g) per square metre.

3.6.2 Leaf water potential

Leaf water potential was recorded using a portable pressure chamber apparatus (Waring and Cleary, 1967). Observation was taken at mid-day (1200 hour) under full sunlight. At crown root initiation stage (CRI), whole plant was taken for measurement after cutting from the ground level. At other growth periods, fully exposed leaf, second from the top, was selected. Three leaves per plant per treatment were sampled and values were averaged for each treatment.

3.6.3 Root studies

Representative wheat plants from three replications (seven tillage treatments each in one replication) on root growth parameters, viz. root length density, root mass density, root porosity, root volume density and rooting depth were selected for root sampling recorded at 30, 60, 90, 120 and 150 days after sowing (DAS) during *Rabi* 2002-03 and 2003-04. Some root parameters were also determined at 120 and 150 DAS in three consecutive soil depths (0.0-0.1, 0.1-0.2 and 0.2-0.3 m).

Metallic cores (0.126 m length and 0.104 m internal diameter) were excavated for root parameters in three replications. The cores were kept in water overnight and then roots were made free from soil by washing with fine spray of water. Roots were collected on fine sieve (1 mm) for a final washing with micro-jet tap and observations for the following parameters were made: -

3.6.3.1 Root length density

Root length was measured in a glass bottomed shallow dish of 0.4 m x 0.2 m dimension using Newman (1966) technique. Graph paper ruled in millimeters was placed under the dish. The wet roots were cut from the root-shoot joint and poured into the dish containing some water. The roots were positioned randomly over the graph paper lines (representing a grid) with the help of a forceps and a needle, so that they did not overlap one another. The long branched roots were cut into smaller pieces. The counts for intersections of roots (N) with vertical and horizontal lines of 1 cm grid from the graph paper were recorded. Care was taken to avoid more than 400 counts at one instance (Kopke, 1979).

Root length was computed using the modified version of Newman (1966) formula as proposed by Marsh (1971) and Tennant (1975): -

Root length (R) = 11/14 x Number of intersections (N) x grid unit (cm)

The grid unit was combined with 11/14 factor, which gave a factor of 0.786 for one grid square. The root length density (RLD) was calculated as root length per unit soil core volume.

Root length density = Total root length (m)/ Volume of the core (m^3)

3.6.3.2 Root mass density

Soil samples were collected with the help of core from each treatment in all the three replications. The roots were washed on 70 mesh sieve with water jet and dried in an oven at 70^0C for three days to determine the root mass. The root mass density (RMD) was calculated as root mass per unit soil core volume.

Root mass density = Oven dry weight of roots (kg)/ Volume of the core (m^3)

Volume of the core was calculating as follows: -

$$V = \Pi r^2 h$$

Where,

V : Volume of the core

Π : 3.14 or 22/7

r : Radius of core (m)

h : Height of the core (m)

3.6.3.3 Root volume density

The volume of the roots was determined by displacement method (Mishra and Ahmed, 1987). For this, the roots were immersed in a marked cylinder filled with distilled water and the volume raised by these roots was recorded for calculating the root volume. This root volume is divided by the volume of the core to compute root volume per unit volume of soil (root volume density). The roots were then transferred to a filter paper and were gently pressed in its folds to remove the imbibed water.

Root volume density = Volume of water displaced (m^3)/ Volume of the core (m^3)

3.6.3.4 Root porosity

The porosity of the roots was calculated by using the Jensen *et al.* (1969) formula as: -

$$\boxed{\textbf{\% Root porosity} = 100\,(W_h - W_{r+w}) / (W_w + W_r - W_{r+w})}$$

Where,

W_{r+w} : Weight of a sample of the roots in Pycnometer bottle filled with water (g)

W_r : Weight of root sample alone (g)

W_w : Weight of the Pycnometer bottle filling with water only (g)

W_h : Weight of the homogenate mixture of the root sample in Pycnometer bottle (g)

3.6.4 Crop yield

The crop from the net plot area was harvested with the help of sickles, and was left in the respective plots for sun drying for 2-3 days. When most of the straw in a handful bundle broke up on folding, then total produce was weighed and recorded as biological yield. The produce was then threshed with thresher and grains were separated out. The grains thus collected were weighed and moisture content in grain samples from all the plots was determined using Universal Moisture Meter. The grain yield recorded as kg per plot was standardized at 14 per cent moisture and was converted into Mg ha^{-1}. The straw yield was obtained by deducting the grain weight from the corresponding weight of the biological produce and was converted into Mg ha^{-1}.

3.7 Meteorological parameters

The meteorological data of the study area pertaining to all the periods of the investigation for temperature, relative humidity, wind velocity, bright sunshine hours, rainfall and evaporation were procured from the Meteorological Observatory of the Department of Agronomy, CSK Himachal Pradesh Krishi Vishvavidyalaya, Palampur located within about 1 km distance from the experimental site.

3.8 Statistical analysis

The data recorded in respect of various observations were subjected to statistical analysis based on analysis of variance techniques as described by Cochran and Cox (1963) to identify the treatment effects and were tested at 5 per cent level of significance to interpret the significance differences.

RESULTS

CHAPTER- IV

EXPERIMENTAL RESULTS

The results obtained from the present investigation entitled, "Soil-water dynamics, root growth and wheat yield in a sequentially deep tilled post-rice soil" have been presented in this chapter through tables and illustrated with the help of figures wherever necessary.

- 4.1 Meteorological parameters
    - 4.1.1 Temperature
    - 4.1.2 Relative humidity
    - 4.1.3 Rainfall
    - 4.1.4 Evaporation
    - 4.1.5 Bright sunshine hours
    - 4.1.6 Wind velocity
- 4.2 Initial soil properties
    - 4.2.1 Particle size distribution
    - 4.2.2 Bulk density
    - 4.2.3 Particle density
    - 4.2.4 Total porosity
    - 4.2.5 Saturated hydraulic conductivity
    - 4.2.6 Infiltration rate
    - 4.2.7 Soil water retention
    - 4.2.8 Plant water available capacity

- 4.2.8 Soil chemical and physico-chemical properties
  - 4.2.8.1 Soil pH
  - 4.2.8.2 Organic carbon
  - 4.2.8.3 Cation exchange capacity
  - 4.2.8.4 Available nutrients
- 4.3 Soil studies
  - 4.3.1 Structural properties
    - 4.3.1.1 Bulk density
    - 4.3.1.2 Soil penetration resistance
  - 4.3.2 Hydraulic properties
    - 4.3.2.1 Soil water content
    - 4.3.2.2 Hydraulic conductivity
      - 4.3.2.2.1 Saturated hydraulic conductivity
      - 4.3.2.2.2 Unsaturated hydraulic conductivity
    - 4.3.2.3 Soil matric potential
    - 4.3.2.4 Hydraulic gradient
    - 4.3.2.5 Hydraulic flux
    - 4.3.2.6 Infiltration rate
  - 4.3.3 Mechanical properties
    - 4.3.3.1 Energy required for land preparation
  - 4.3.4 Soil temperature
- 4.4 Plant observations
  - 4.4.1 Plant growth parameters
    - 4.4.1.1 Emergence count

4.4.1.2 Seedling emergence parameters
4.4.1.3 Plant height
4.4.1.4 Number of tillers
4.4.1.5 Dry matter accumulation
4.4.2 Leaf water potential
4.4.3 Root studies
4.4. 3.1 Root mass density
4.4.3.2 Root length density
4.4.3.3 Root volume density
4.4.3.4 Root porosity
4.4.3.5 Rooting depth
4.4.4 Crop yield

4.1 Meteorological parameters

Meteorological data of the study area pertaining to the periods of study, recorded at a nearby university weather station, have been appended in appendices I and II and illustrated graphically in Figure 4.1, 4.2, 4.3 and 4.4.

4.1.1 Temperature

The maximum air temperature varied from 10.0 to 32.0^{0}C and 8.4 to 33.0^{0}C and the corresponding ranges of a minimum temperature from 1.0 to 22.0^{0}C and 1.8 to 18.3^{0}C in 2002-03 and 2003-04 (Figure 4.1 and 4.3), respectively.

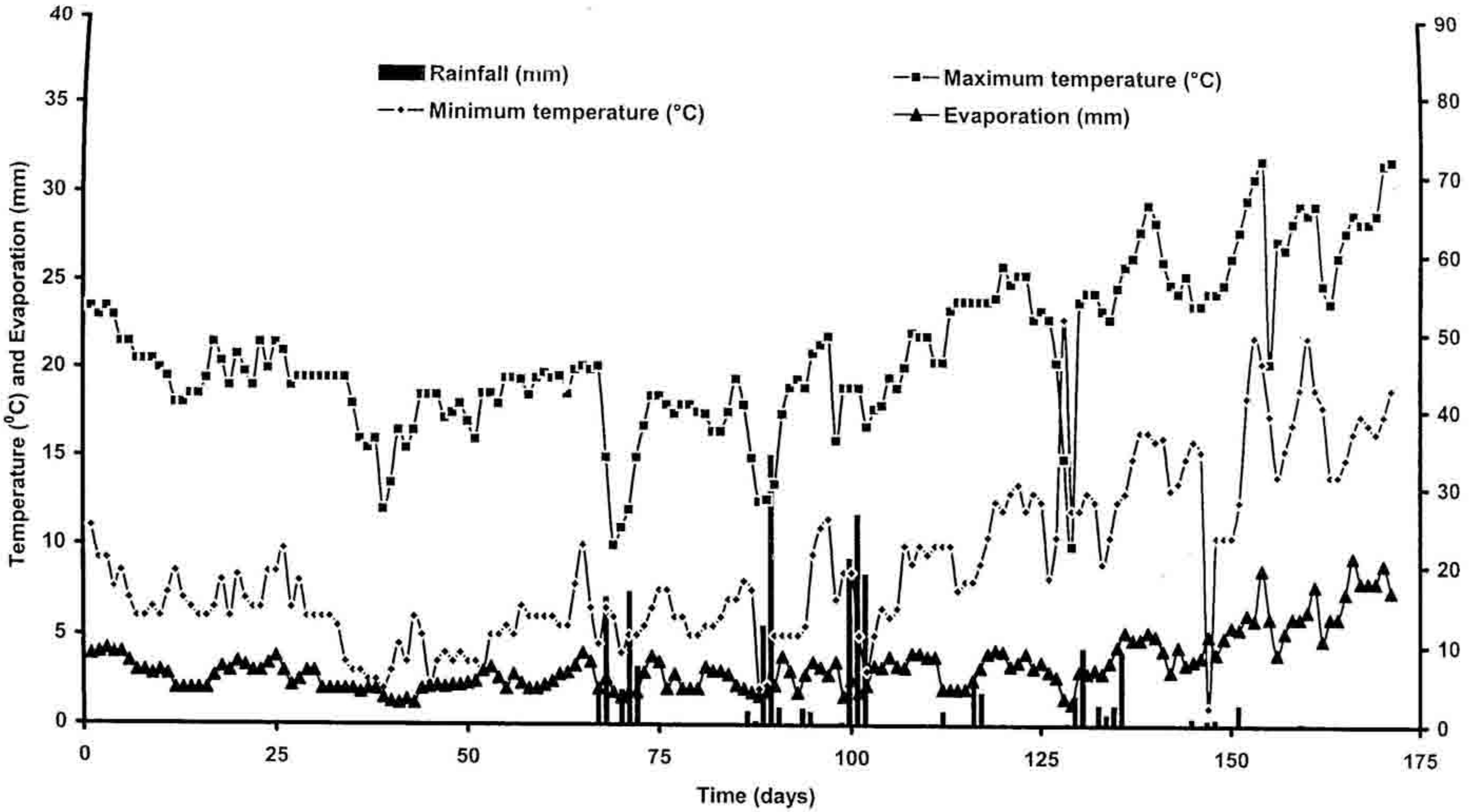


Figure 4.1: Daily rainfall, temerature and evaporation data of Palampur for the first wheat crop season (2002- 03)

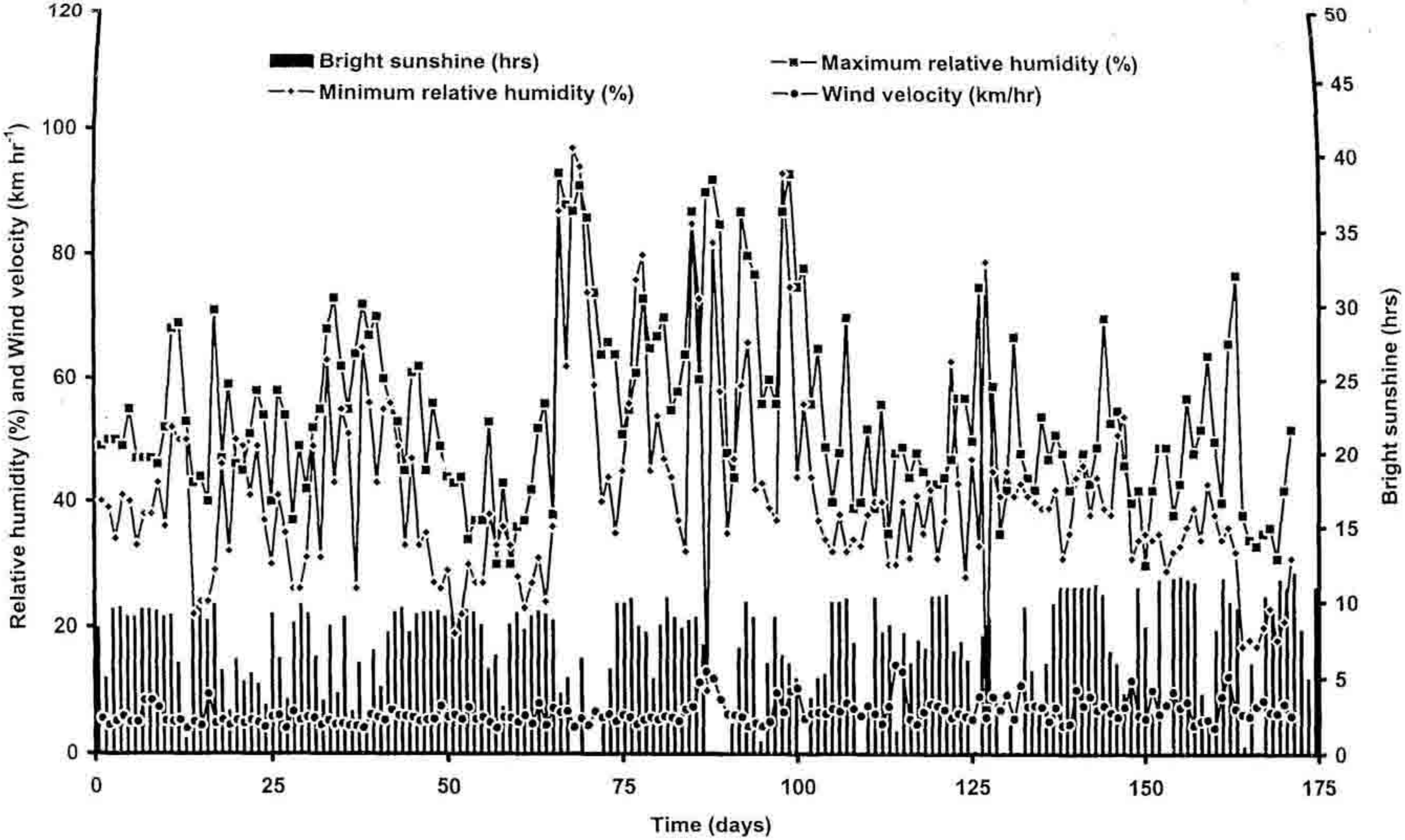


Figure 4.2: Daily relative humidity, wind velocity and bright sunshine hours of Palampur for the first wheat crop season (2002- 03)

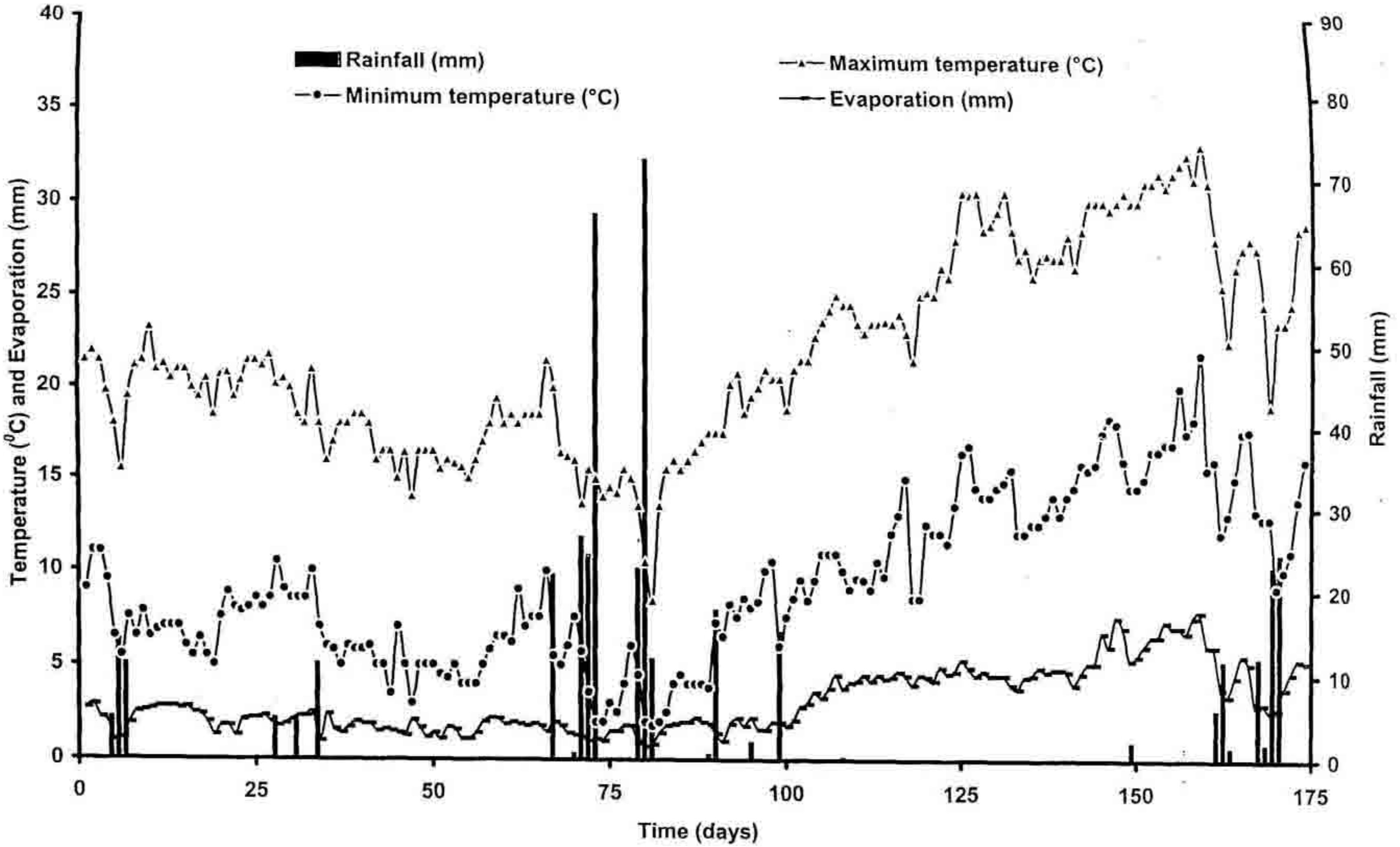


Figure 4.3: Daily rainfall, temperature and evaporation data of Palampur for the second wheat crop season (2003- 04)

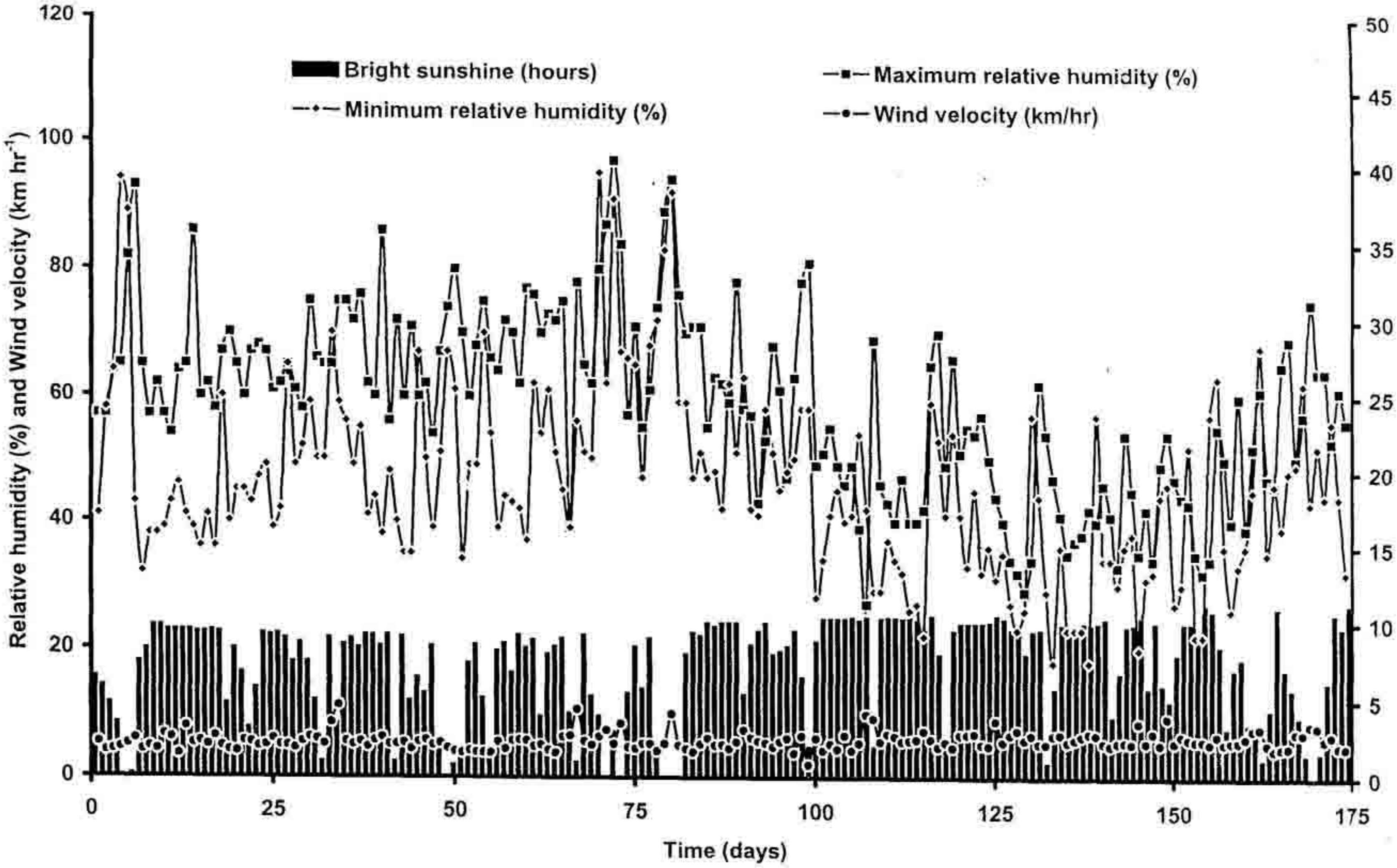


Figure 4.4: Daily relative humidity, wind velocity and bright sunshine hours data of Palampur for second wheat crop season (2003- 04)

4.1.2 Relative humidity

The maximum relative humidity (Figure 4.2 and 4.4) was observed on March 2, 2003 (93%) and January 1, 2004 (97%) and minimum (10 per cent) on (February 18, 2003), and 18 per cent on (March 30, 2004).

4.1.3 Rainfall

During 2002-03 study period, 32 rainy days accounted for 209.5 mm of rainfall, and during 2003-04 study period, total rainfall received was 417.3 mm in 28 rainy days (Figure 4.1 and 4.3).

4.1.4 Evaporation

Total open pan evaporation during both wheat crop seasons i.e. 2002-03 and 2003-04 was 572.9 mm and 536.2 mm (Figure 4.1 and 4.3), respectively.

4.1.5 Bright sunshine hours (BSS)

The maximum BSS were 12.0 hours on May 10, 2003 and April 15, 2003 and 11.2 hours for May 5, 2004 during both years of the crop study (Figure 4.2 and 4.4).

4.1.6 Wind velocity

The wind velocity varied from 4.0 to 13.0 km hr^{-1} during the first year of the study and in second year, it varied from 2.0 to 11.2 km hr^{-1} (Figure 4.2 and 4.4), respectively.

4.2 Initial soil properties

4.2.1 Particle size distribution

A perusal of Table 4.1 showed that the silt content was the highest (52.1%) in 0.00-0.15 m followed by 49.1 per cent in 0.15-0.30 m and 48.3 per cent in

0.30-0.45 m soil depth; clay content was the highest (29.4%) in 0.15-0.30 m and sand was the highest (24.4%) in 0.00-0.15 m layer. The textural class was silty clay loam for the 0.00-0.15, 0.15-0.30 and 0.30-0.45 m depths.

4.2.2 Bulk density

The highest value of bulk density (1.35 Mg m^{-3}) was observed for 0.30-0.45 m depth and lowest (1.24 Mg m^{-3}) for surface 0.00-0.15 m depth (Table 4.1).

4.2.3 Particle density

The particle density was lowest (2.54 Mg m^{-3}) in 0.00-0.15 m and highest (2.57 Mg m^{-3}) in 0.30-0.45 m soil layer, respectively as given in Table 4.1.

4.2.4 Total porosity

The porosity was highest (51.2%) in 0.00-0.15 m and lowest (47.5%) in 0.30-0.45 m layer, respectively as shown in Table 4.1.

4.2.5 Saturated hydraulic conductivity

Saturated hydraulic conductivity values determined in the laboratory for 0.00-0.45 m profile depth showed a decreasing trend from 2.01×10^{-6} to 1.29×10^{-6} m s^{-1} with depth (Table 4.1).

4.2.6 Infiltration rate

The steady state infiltration rate was 0.92 cm hr^{-1} for the study site (Table 4.1).

4.2.7 Soil water retention

Volumetric water content (θ) in all the layers decreased with increase in suction (Ψ). The 'θ' values for 0.00-0.15 m soil layer at 0, 33.3 and 1500 kPa suctions was 45.3, 30.4 and 18.3 per cent and 55.6, 40.3 and 23.5 per cent for soil depth 0.30-0.45 m, respectively. The water retention increased with depth at all suction values (Table 4.1).

Table 4.1: Important physical, chemical and physico-chemical properties of experimental soil at the initiation of experiment

Sr. No.	Parameters	Soil depth (m)		
		0.00-0.15	0.15-0.30	0.30-0.45
1.	Particle size distribution			
	I. Clay (%)	23.2	29.4	27.3
	II. Silt (%)	52.1	49.1	48.3
	III. Sand (%)	24.4	20.2	24.1
2.	Textural class	Silty clay loam	Silty clay loam	Silty clay loam
3.	Bulk density (Mg m^{-3})	1.24	1.29	1.35
4.	Particle density (Mg m^{-3})	2.54	2.56	2.57
5.	Porosity (%)	51.2	49.6	47.5
6.	Saturated hydraulic conductivity (x 10^{-6} m s^{-1})	2.01	1.63	1.29
7.	Steady state infiltration (cm hr^{-1})	0.92		
8.	Soil water retention (%)			
	I. 0 kPa	45.3	51.2	55.6
	II. 33.3 kPa	30.4	35.4	40.3
	III. 1500 kPa	18.3	21.3	23.5
9.	Plant available water capacity (%)	12.1	14.1	16.8
10.	pH (1: 2.5)	5.6	5.4	5.0
11.	Organic carbon (%)	0.73	0.58	0.41
12.	Cation exchange capacity [cmol(p+) kg^{-1}]	9.7	7.9	6.9
13.	Available nutrients (kg ha^{-1})			
	I. Available nitrogen	294	251	218
	II. Available phosphorous	20.4	16.2	12.9
	III. Available potassium	185	139	108

4.2.8 Plant water available capacity

A plant water available capacity was higher (16.8%) in 0.30-0.45 m and lower (12.1%) in 0.00-0.15 m soil depth (Table 4.1).

4.2.8 Soil chemical and physico-chemical properties

4.2.8.1 Soil pH

The soil of the experimental site was acidic in reaction with a pH of 5.6 at 0.00-0.15 m followed by 5.4 and 5.0 in 0.15-0.30 and 0.30-0.45 m soil depth (Table 4.1), respectively.

4.2.8.2 Organic carbon

The organic carbon content of the soil decreased with increased in depth (Table 4.1). It was highest (0.73%) in 0.00-0.15 m and lowest (0.41%) in 0.30-0.45 m soil layer, respectively.

4.2.8.3 Cation exchange capacity

The cation exchange capacity value of the experimental soil was highest 9.7 cmol(p+) kg^{-1} in 0.00-0.15 m layer followed by 7.9 and 6.97 cmol(p+) kg^{-1}, for 0.15-0.30 and 0.30-0.45 m depths, respectively (Table 4.1).

4.2.8.4 Available nutrients

The soil was medium to low in available nitrogen, phosphorous and potassium contents with values 294, 20.4 and 185 kg ha^{-1} in 0.00-0.15 m and decreased to 218, 12.9 and 108 kg ha^{-1} in 0.30-0.45 m soil depth, respectively as given in Table 4.1.

4.3 Soil studies

4.3.1 Structural properties

4.3.1.1 Bulk density

The bulk density (ρ_b) values determined at sowing and harvest under different tillage treatments of both wheat crops (2002-03 and 2003-04) in 0.0-0.1, 0.1-0.2, 0.2-0.3 and 0.3-0.4 m soil depths are depicted graphically in Figure 4.5, 4.6, 4.7 and 4.8, respectively. In general, 'ρ_b' values increased with depth in both the years of the study.

It is evident from the Figure 4.5 that at the time of sowing, 'ρ_b' values for 0.0-0.1 m depth was significantly lower in treatment T_4 (at par with T_3, T_6 and T_7) as compared to T_1, T_2 and T_5. At 0.1-0.2, 0.2-0.3 and 0.3-0.4 m depths, 'ρ_b' values was significantly lower in T_4 as compared to T_1, T_2, T_3, T_5 and T_6, which remained statistically at par with T_7, respectively. At the time of harvesting, 'ρ_b' values was statistically at par in treatments T_4 and T_7, but was significantly lower as compared to T_1, T_2, T_3, T_5 and T_6, respectively to all the soil depths (Figure 4.6).

During second year of the study (Figure 4.7), 'ρ_b' values (0.0-0.1 and 0.1-0.2 m soil depths) at the time of sowing was significantly lower in treatment T_4 as compared to T_1, T_2, T_5, T_6 and T_7, but remained statistically at par with T_3. At 0.2-0.3 and 0.3-0.4 m depths, treatment T_4 had significantly lower 'ρ_b' values as compared to T_1, T_2, T_3, T_5, T_6 and T_7, respectively. Similar trend was observed in 'ρ_b' values with T_4 at the time of harvesting of second wheat crop

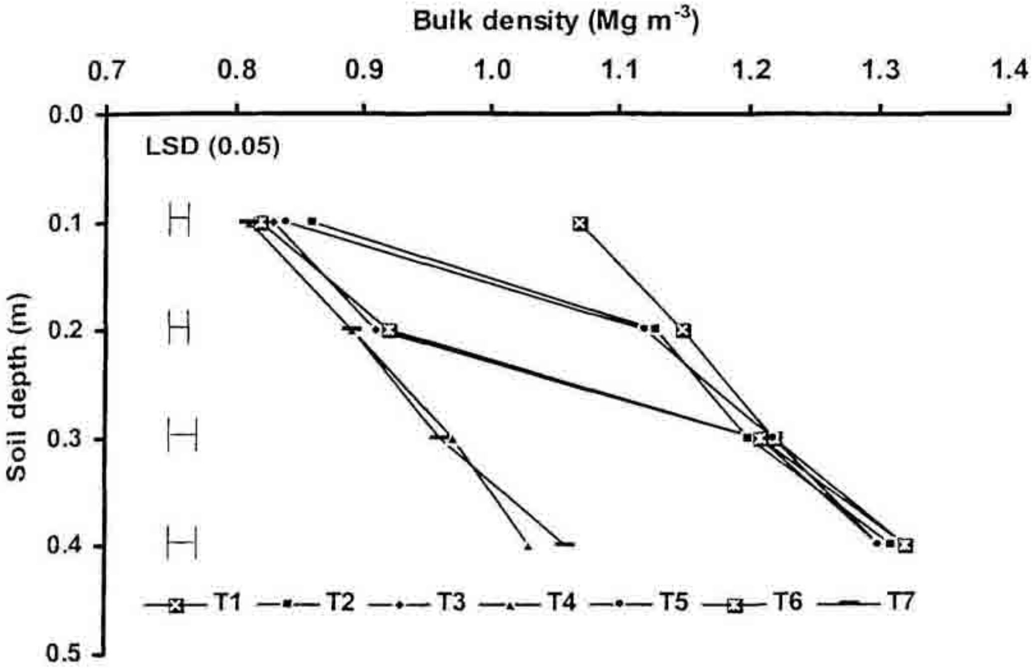


Figure 4.5: Depth-wise bulk density under different tillage treatments at the time of sowing of first wheat crop season (2002- 03)

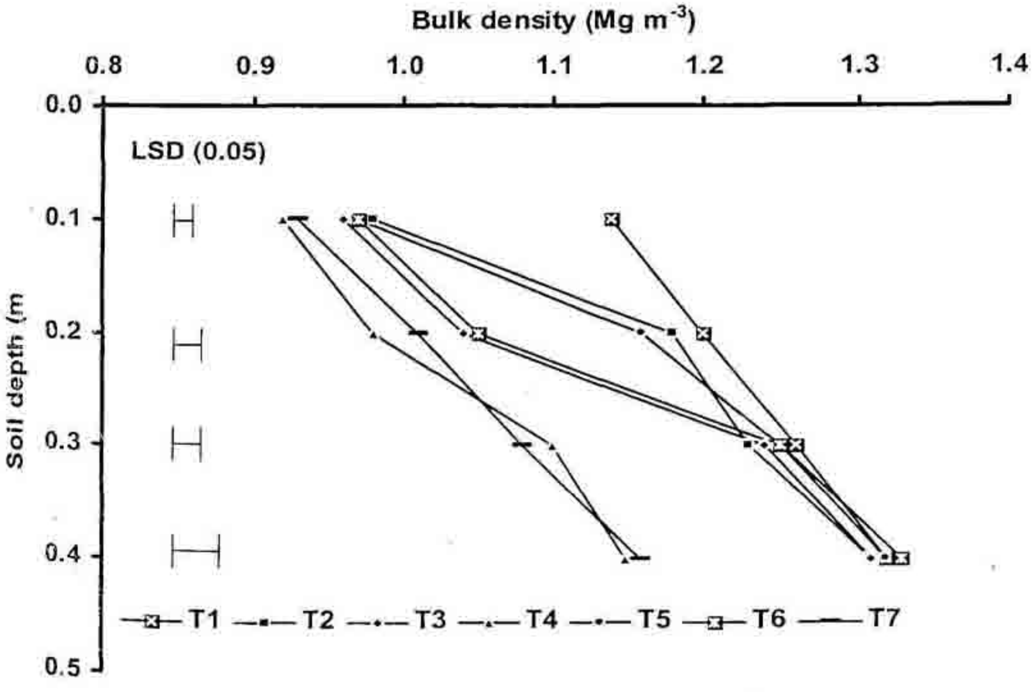


Figure 4.6: Depth-wise bulk density under different tillage treatments at the time of harvesting of first wheat crop season (2002- 03)

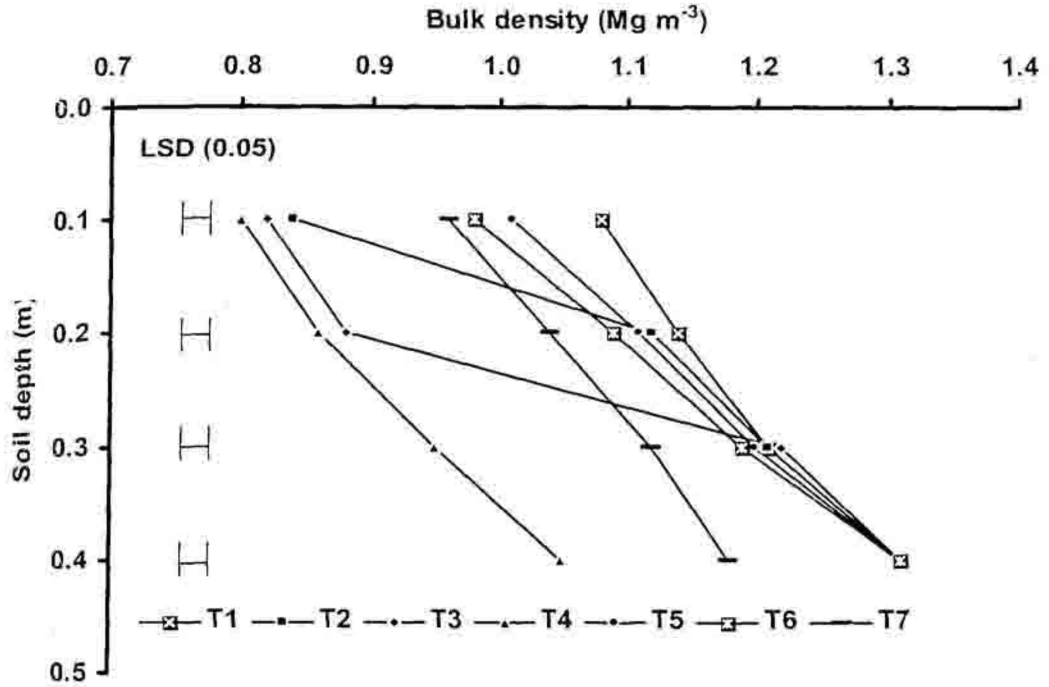


Figure 4.7: Depth-wise bulk density under different tillage treatments at the time of sowing of second wheat crop season (2003- 04)

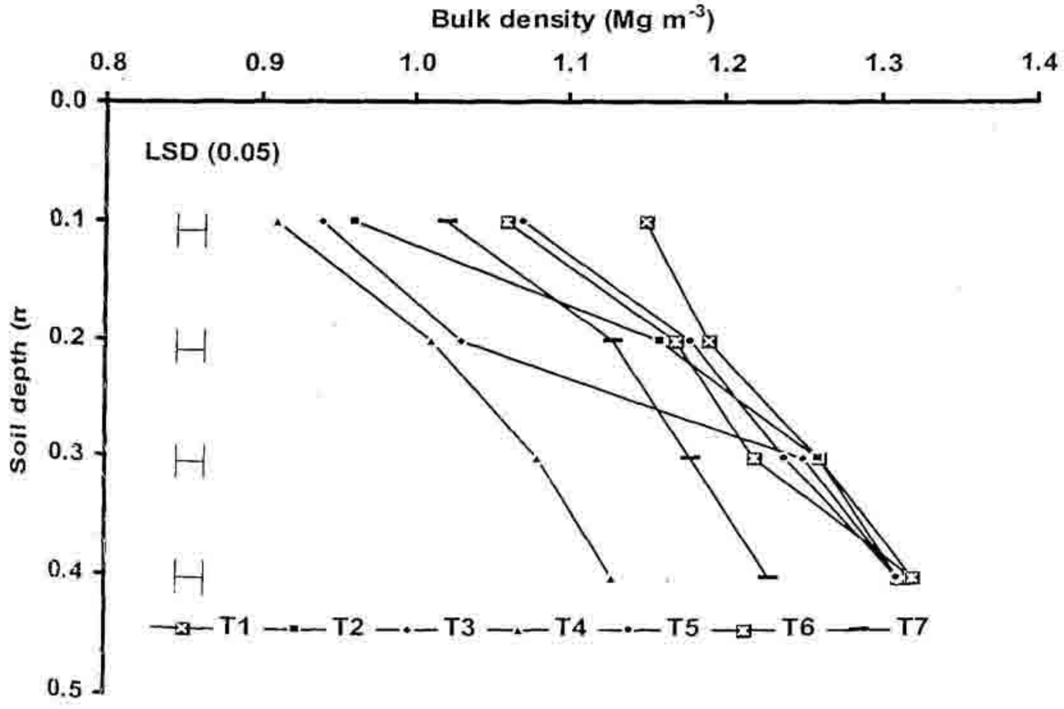


Figure 4.8: Depth-wise bulk density under different tillage treatments at the time of harvesting of second wheat crop season (2003- 04)

(Figure 4.8). At harvest of second wheat crop, treatment T_7 had significantly lower 'ρ_b' values as compared to T_1, T_2, T_3, T_5, and T_6 at 0.2-0.3 and 0.3-0.4 m depths. However, at 0.0-0.1 and 0.1-0.2 m soil depths, the 'ρ_b' values were significantly lower as compared to T_1, T_5 and T_6, respectively. In both the year of study, T_4 had significantly lower and T_1 was higher 'ρ_b' value at sowing and harvest of wheat crops.

4.3.1.2 Soil penetration resistance

The soil penetration resistance (SPR) values determined after first irrigation, at flowering stage and harvest under different tillage treatments of both wheat crop seasons (2002-03 and 2003-04) at different soil depths (0.00-0.03, 0.06-0.09, 0.12-0.15 and 0.18-0.21 m) are presented in Figure 4.9, 4.10, 4.11, 4.12, 4.13 and 4.14, respectively. In general, SPR values decreased with tillage and moisture content in both the years of the study. The treatment T_7 had significantly lower SPR values and the higher SPR values were, however, observed in T_1 in both the years of the study.

During first year of the study (2002-03), the SPR values (0.00-0.03 and 0.06-0.09 m depths) were significantly lower for T_4 (at par with T_2, T_3, T_5, T_6 and T_7) than T_1 after first irrigation (Figure 4.9). At 0.12-0.15 m depth, the SPR values after first irrigation were significantly lower for T_4 (at par with T_3, T_6 and T_7) as compared to T_1, T_2 and T_5. The SPR values for 0.18-0.21 m depth were significantly lower for T_4 (at par with T_7) as compared to T_1, T_2, T_3, T_5 and T_6. Similar trend was also observed at flowering stage in first wheat crop study (Figure 4.10). At harvest of first wheat crop (Figure 4.11), the SPR values for

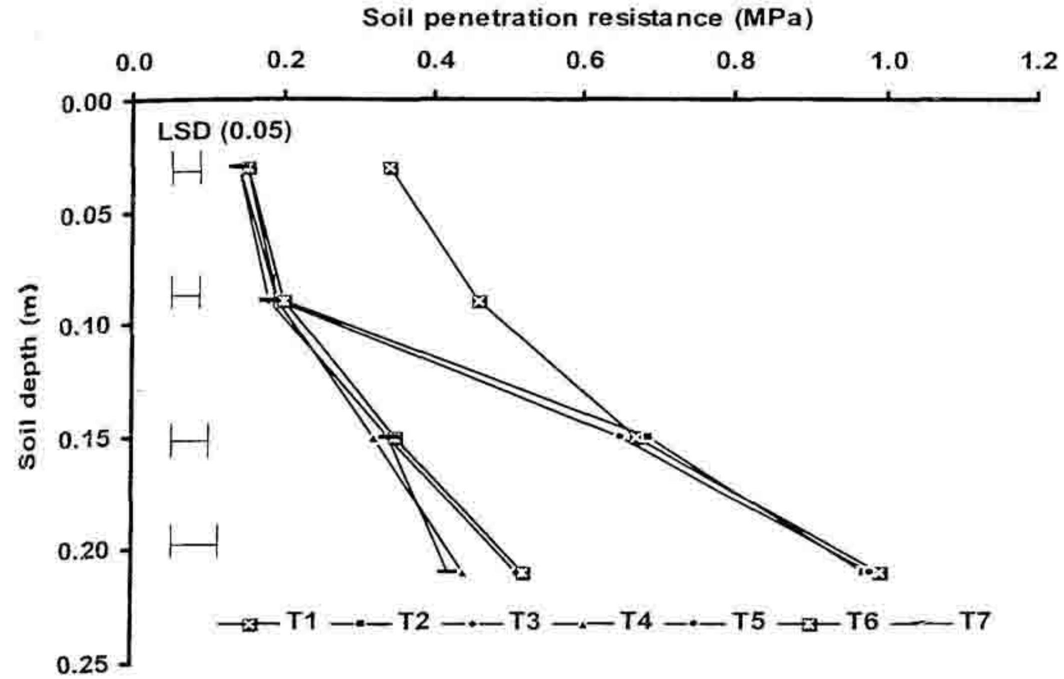


Figure 4.9: Depth-wise soil penetration resistance after first irrigation under different tillage treatments of first wheat crop season (2002- 03)

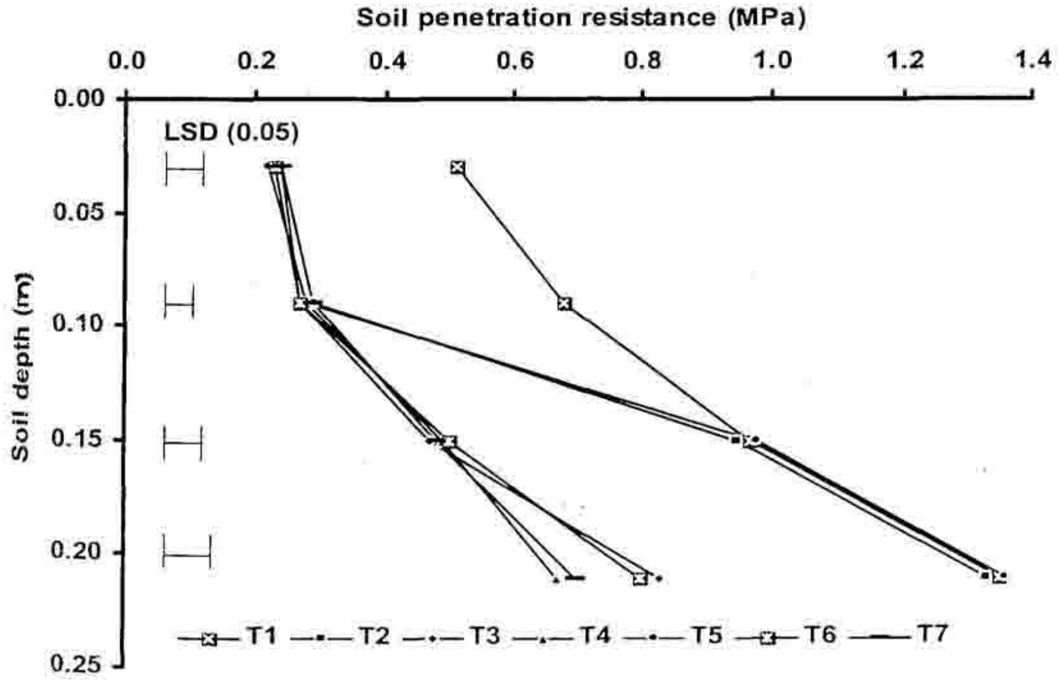


Figure 4.10: Depth-wise soil penetration resistance at flowering stage under different tillage treatments of first wheat crop season (2002- 03)

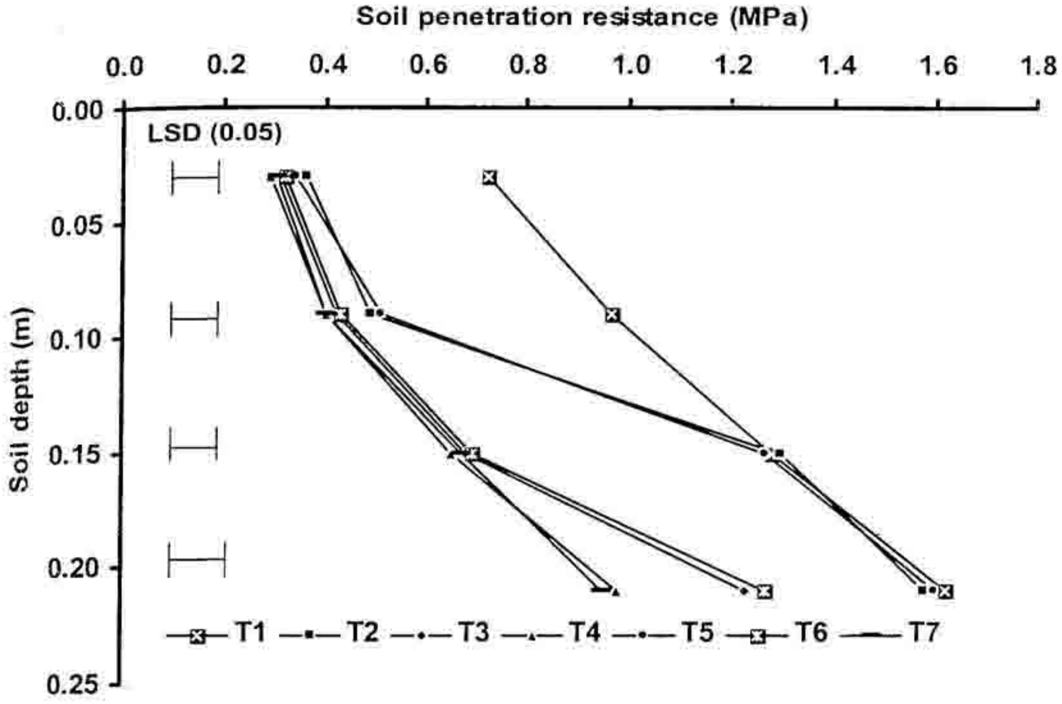


Figure 4.11: Depth-wise soil penetration resistance after harvesting under different tillage treatments of first wheat crop season (2002- 03)

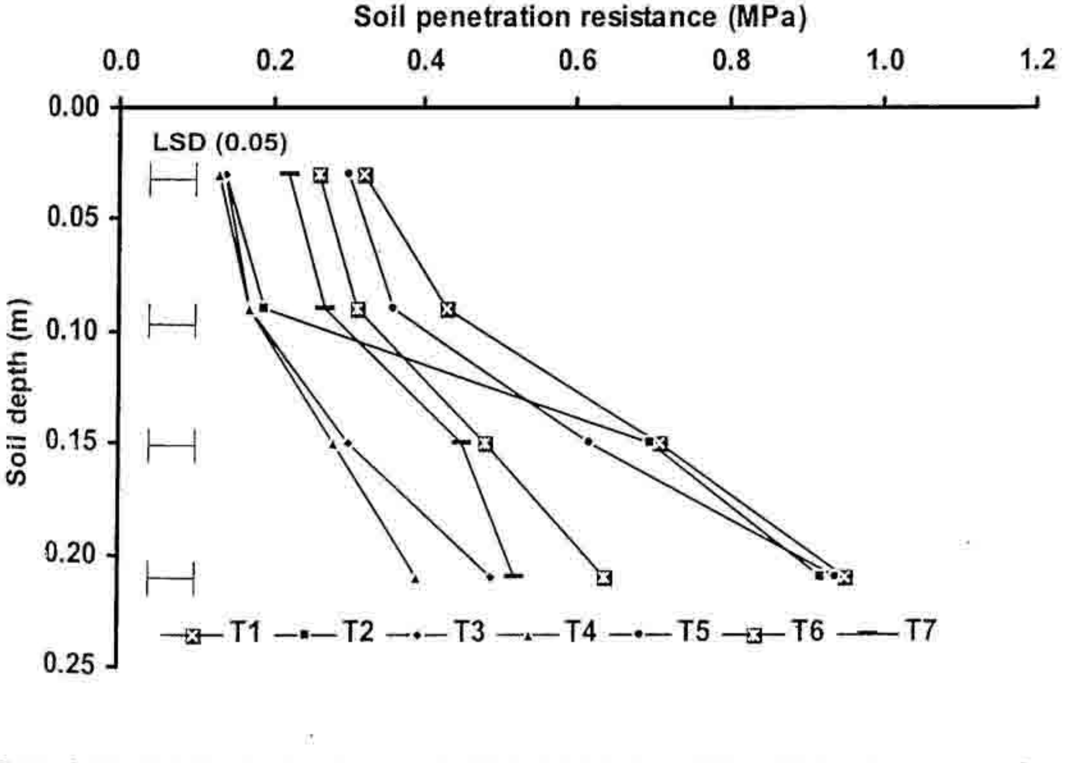


Figure 4.12: Depth-wise soil penetration resistance after first irrigation under different tillage treatments of second wheat crop season (2003- 04)

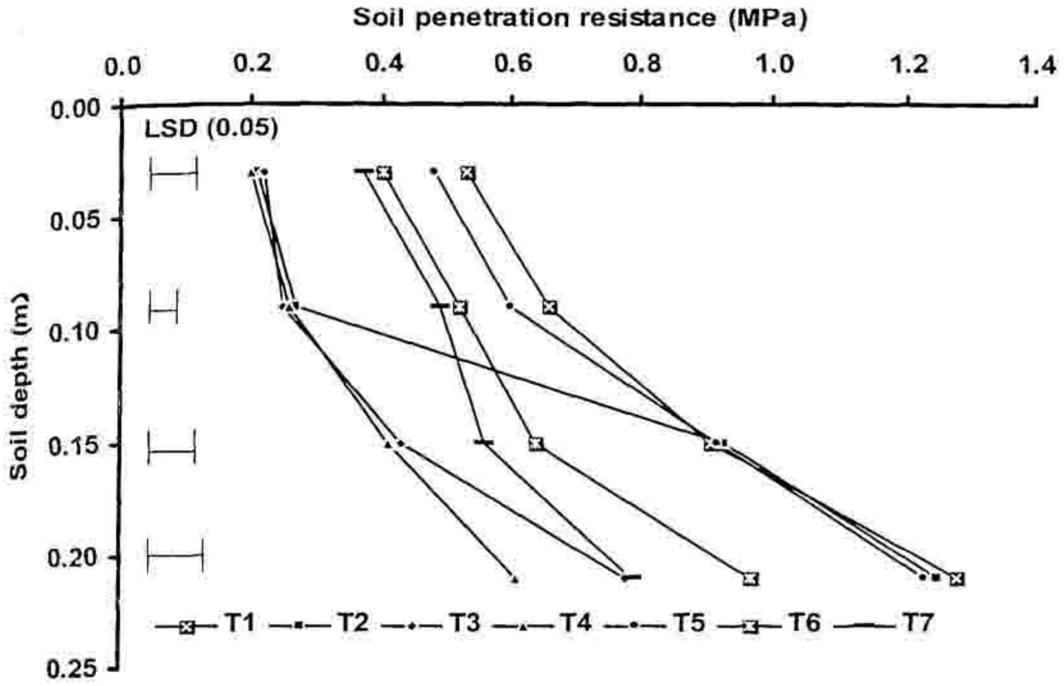


Figure 4.13: Depth-wise soil penetration resistance at flowering stage under different tillage treatments of second wheat crop season (2003- 04)

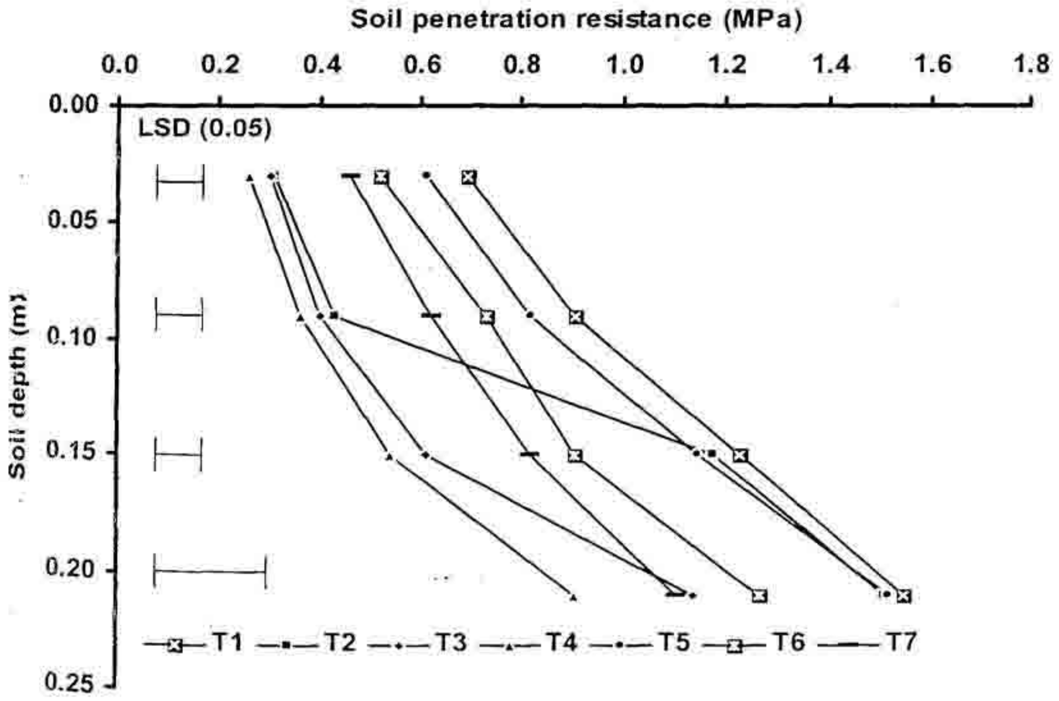


Figure 4.14: Depth-wise soil penetration resistance after harvesting under different tillage treatments of second wheat crop season (2003- 04)

0.00-0.03, 0.06-0.09 and 0.12-0.15 m depth were significantly lower for T_4 (at par with T_3, T_6 and T_7) as compared to T_1, T_2 and T_5, whereas for 0.18-0.21 m depth, T_4 (at par with T_7) had significantly lower SPR values as compared to T_1, T_2, T_3, T_5 and T_6.

It is evident from the Figure 4.12 that the SPR values during second wheat crop season (2003-04) for 0.00-0.03 and 0.06-0.09 m depths were significantly lower in treatment T_4 as compared to T_1, T_5, T_6 and T_7, but remained statistically at par with T_2 and T_3. The next higher was T_7 which was statistically at par with treatment T_6, but significantly different from T_1, T_5 and T_6. At 0.12-0.18 m depth, the SPR values were significantly lower in treatment T_4 (at par with T_3) as compared to T_1, T_2, T_5, T_6 and T_7, whereas T_7 which was statistically at par with treatment T_6, but significantly different from T_1, T_5 and T_6. The SPR values for 0.18-0.21 m depth were significantly lower for T_4 as compared to T_1, T_2, T_3, T_5, T_6 and T_7. However, treatment T_7 (at par with T_3) had significantly lower SPR values than T_1, T_2, T_5 and T_6. Similar trend was observed at flowering and harvest stage of first wheat growing season (Figure 4.13 and 4.14), except in 0.12-0.15 m depth at harvest where the SPR values were significantly lower in treatment T_4 as compared to all other treatments.

4.3.2 Hydraulic properties

4.3.2.1 Soil water content

The volumetric water content (θ) determined at sowing and harvest under different tillage treatments of both wheat crops (2002-03 and 2003-04) in 0.0-0.1, 0.1-0.2, 0.2-0.3 and 0.3-0.4 m soil layers are depicted graphically in

Figure 4.15, 4.16, 4.17 and 4.18, respectively. In both the year of study, T_4 had significantly lower and T_1 had higher 'θ' values at sowing and harvest of wheat crops.

It is evident from the Figure 4.15 that at the time of sowing, 'θ' values during the first year of the study for 0.0-0.1 m soil depth was significantly higher in treatment T_1 as compared to T_2, T_3, T_4, T_5, T_6 and T_7. At 0.1-0.2 m soil depth, 'θ' values were significantly higher in T_1 (at par with T_2 and T_5) than T_3, T_4, T_6 and T_7. However, at 0.2-0.3 and 0.3-0.4 m soil layer, 'θ' values were significantly higher in T_1 (at par with T_2, T_3, T_5 and T_6) than T_4 and T_7. Similar trend was also observed at the harvest of the study (Figure 4.16).

During second year of the study, 'θ' values for 0.0-0.1 m soil depths at the time of sowing (Figure 4.17) were significantly higher in treatment T_1 as compared to T_2, T_3, T_4 and T_7, but remained statistically at par with T_5 and T_6. At 0.1-0.2 m depth, treatment T_1 (at par with T_2, T_5 and T_6) had significantly higher 'θ' values as compared to T_3, T_4 and T_7, respectively. However, at 0.2-0.3 and 0.3-0.4 m soil layer, 'θ' values were significantly higher in T_1 (at par with T_2, T_3, T_5 and T_6) than T_4 and T_7. At the harvest of second wheat crop (Figure 4.18), 'θ' values for 0.0-0.1 m soil depth were significantly higher in treatment T_1 (at par with T_2, T_5, T_6 and T_7) as compared to T_3 and T_4, respectively. Similarly, at 0.1-0.2 m soil depth, 'θ' values were significantly higher in treatment T_1 (at par with T_2 and T_5) as compared to T_3, T_4, T_6 and T_7, respectively. Further, treatment T_1 (at par with T_2, T_3, T_5, T_6 and T_7) had significantly higher 'θ' values compared to T_4 at 0.2-0.3 and 0.3-0.4 m soil layer, respectively.

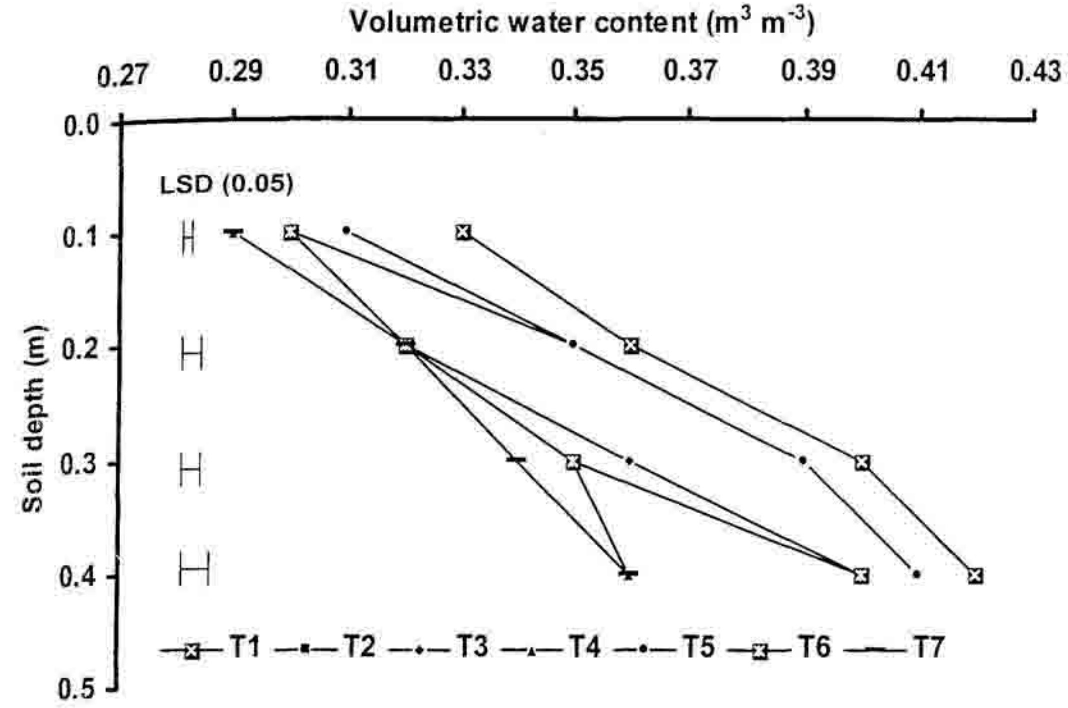


Figure 4.15: Depth-wise soil water content under different tillage treatments at the time of sowing of first wheat crop season (2002- 03)

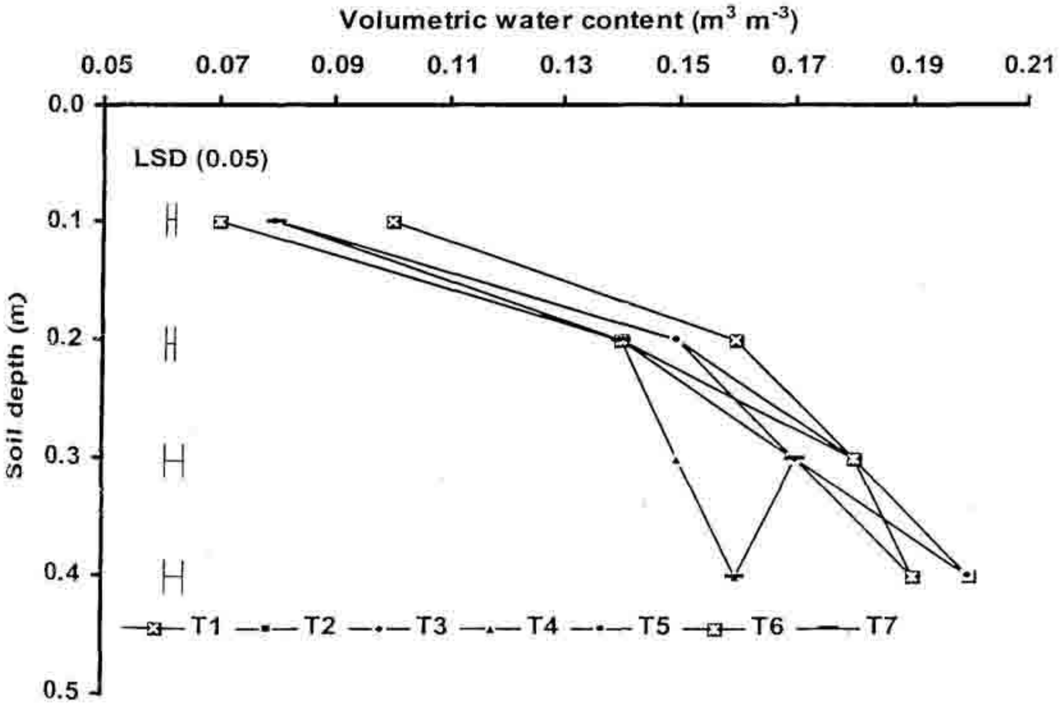


Figure 4.16: Depth-wise soil water content under different tillage treatments at the time of harvesting of first wheat crop season (2002- 03)

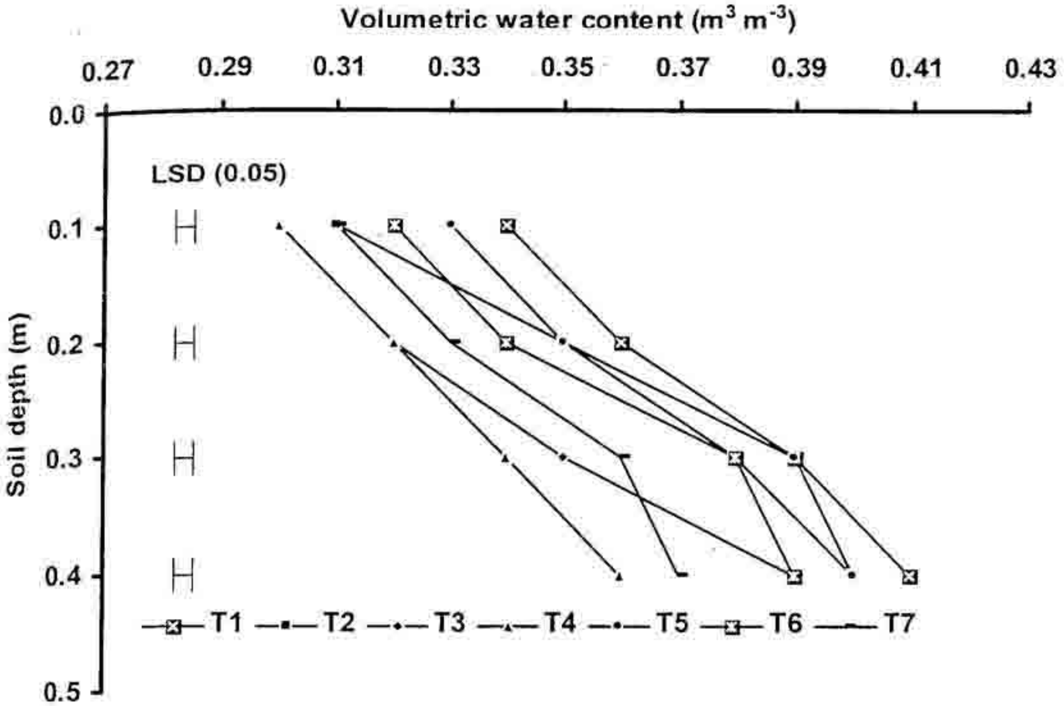
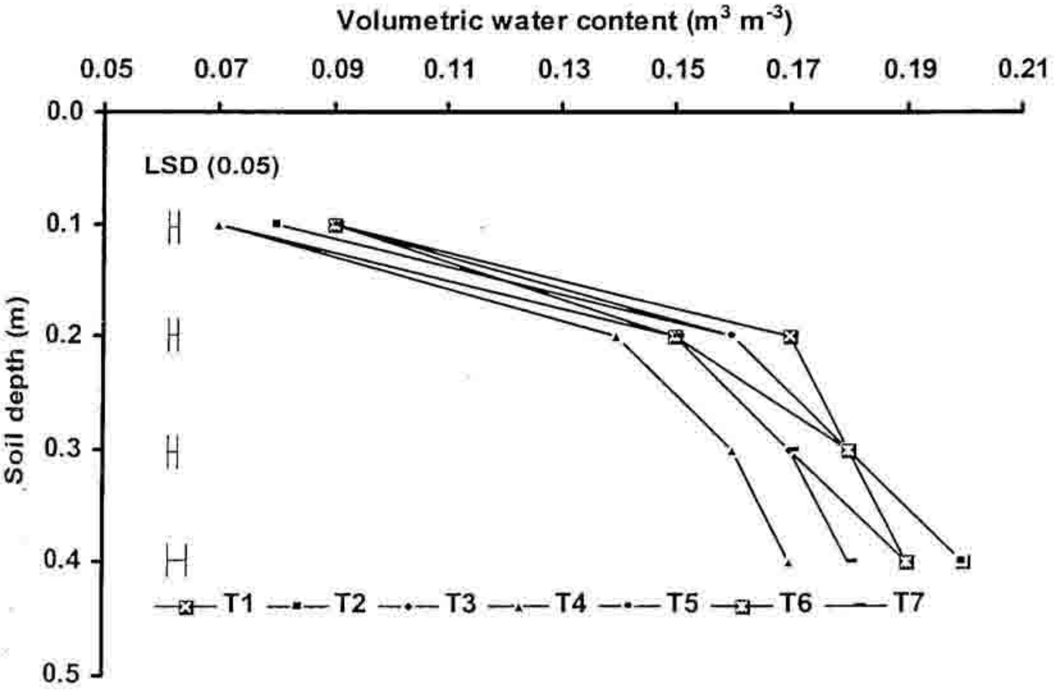


Figure 4.17: Depth-wise soil water content under different tillage treatments at the time of sowing of second wheat crop season (2003- 04)



igure 4.18: Depth-wise soil water content under different tillage treatments at the time of harvesting of second wheat crop season (2003- 04)

The changes in water content with time under different tillage treatments (T_1, T_2, T_3, T_4, T_5, T_6 and T_7) at four consecutive soil depths (0.0-0.1, 0.1-0.2, 0.2-0.3 and 0.3-0.4 m soil depths) during both the wheat crop seasons (2002-03 and 2003-04) are presented in Figure 4.19, 4.20, 4.21, 4.22, 4.23, 4.24, 4.25, 4.26, 4.27, 4.28, 4.29, 4.30, 4.31 and 4.32. During first year of the wheat crop season (2002-03), the 'θ' values in all the four consecutive depths at 20 days after sowing (DAS) were higher in T_4 and T_7 treatments as compared to T_1, T_2, T_3, T_5, and T_6. Further, the 'θ' value was higher in T_1 as compared to T_2, T_3, T_4, T_5, T_6 and T_7 in all the soil depths when there were rainless periods. On 87 DAS (34.0 mm rainfall), the 'θ' values for 0.0-0.1, 0.1-0.2, 0.2-0.3 and 0.3-0.4 m soil depths were higher in T_4 and T_7 as compared to T_1, T_2, T_3, T_5 and T_6 (Figure 4.19, 4.20, 4.21, 4.22, 4.23, 4.24 and 4.25).

During the second year of the study (2002-03), the 'θ' values at 27 DAS were higher in T_4 as compared to T_1, T_2, T_3, T_5, T_6 and T_7 treatments when first irrigation of 5 cm was applied one day before During the second year also, the 'θ' value was higher in T_1 as compared to T_2, T_3, T_4, T_5, T_6 and T_7 in all the soil depths when there were rainless periods. On 79 DAS (72.5 mm rainfall), the 'θ' values for 0.0-0.1, 0.1-0.2, 0.2-0.3 and 0.3-0.4 m soil depths were higher in T_4 as compared to T_1, T_2, T_3, T_5, T_6 and T_7 (Figure 4.26, 4.27, 4.28, 4.29, 4.30, 4.31 and 4.32).

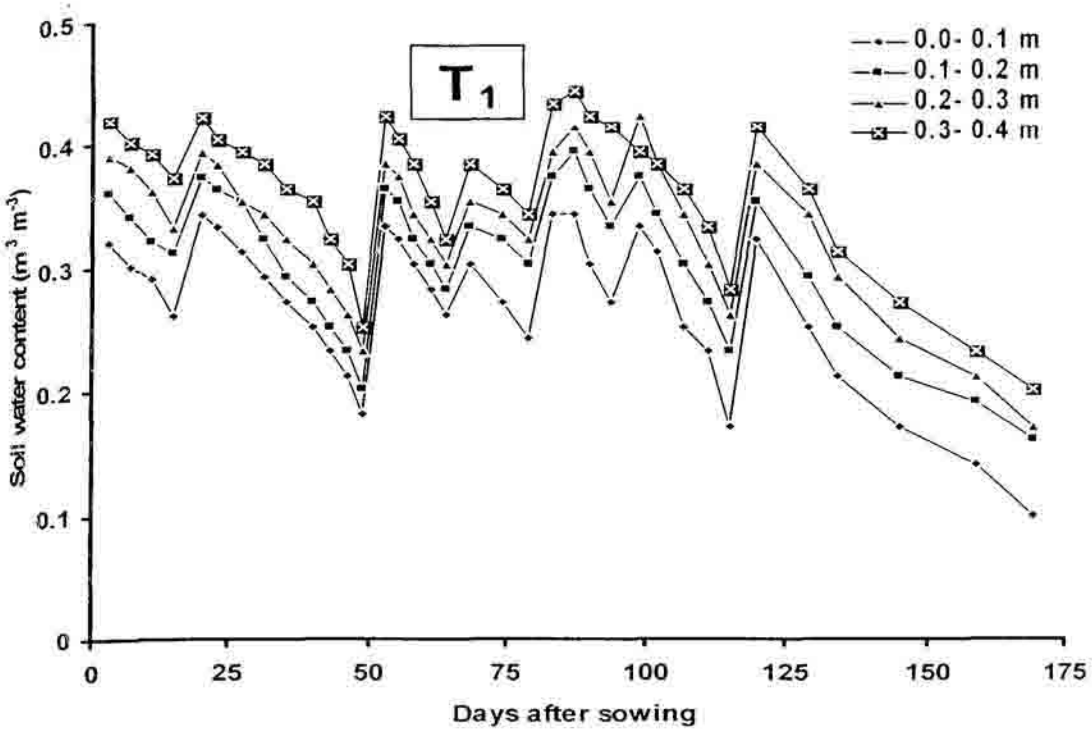


Figure 4.19: Changes in soil water content with time under tillage treatment T_1 at different depths (m) for the first wheat crop season (2002- 03)

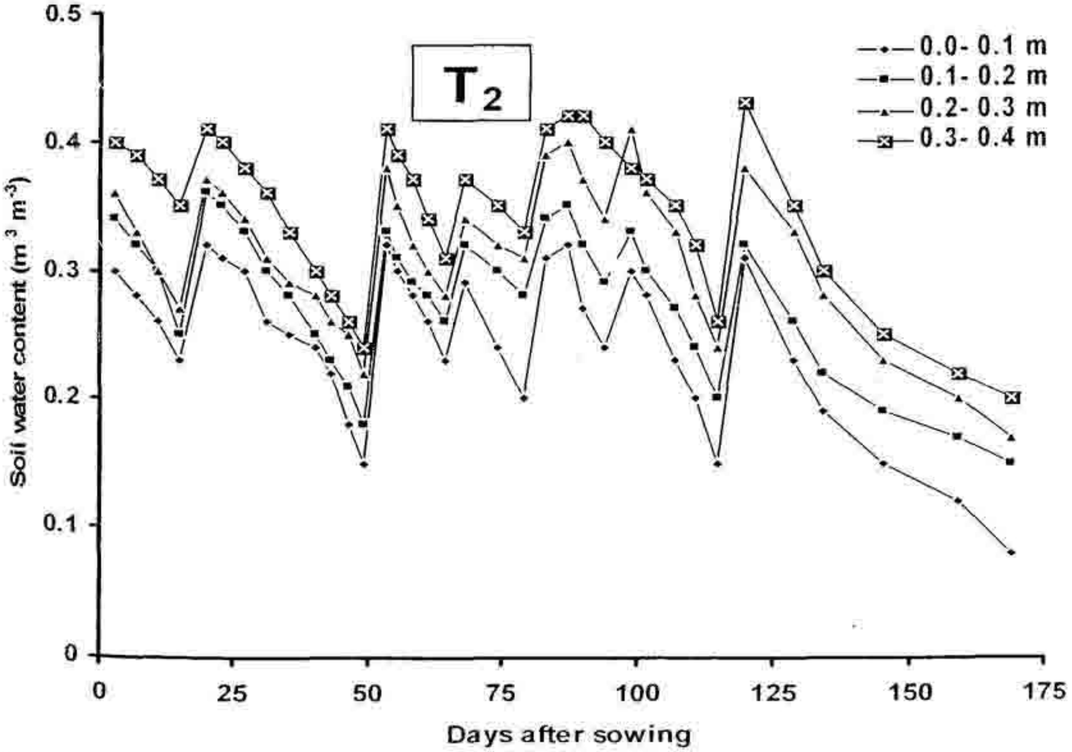


Figure 4.20: Changes in soil water content with time under tillage treatment T_2 at different depths (m) for the first wheat crop season (2002- 03)

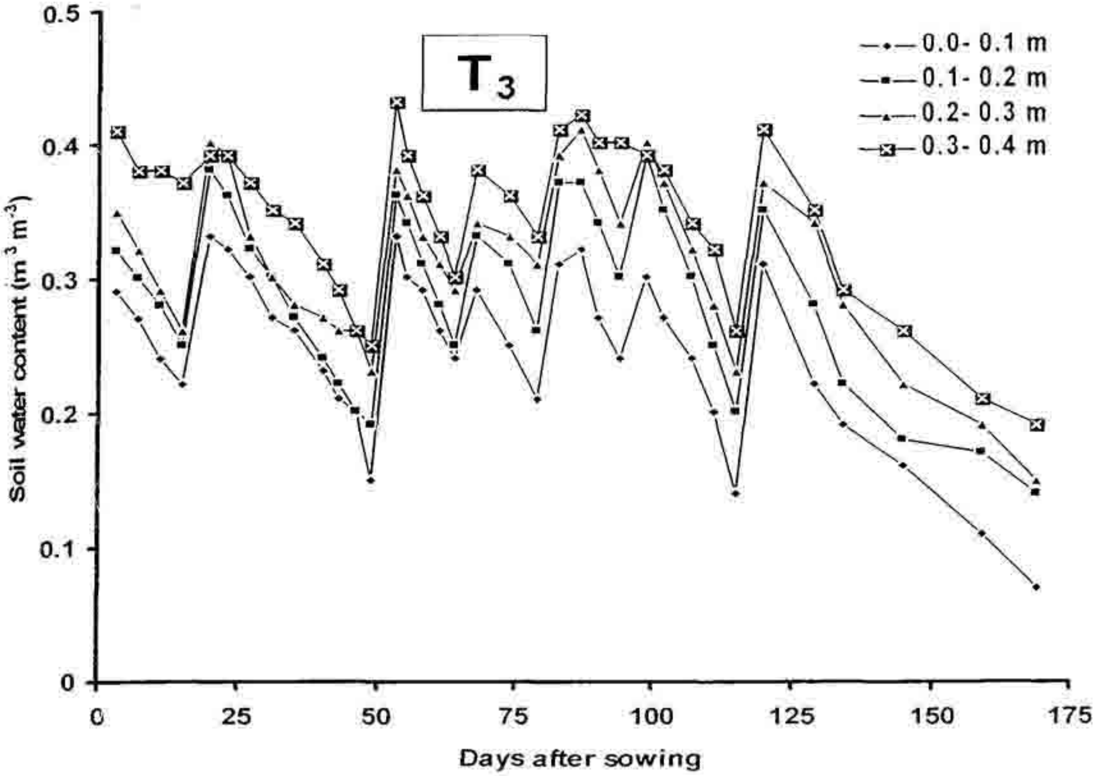


Figure 4.21: Changes in soil water content with time under tillage treatment T_3 at different depths (m) for the first wheat crop season (2002- 03)

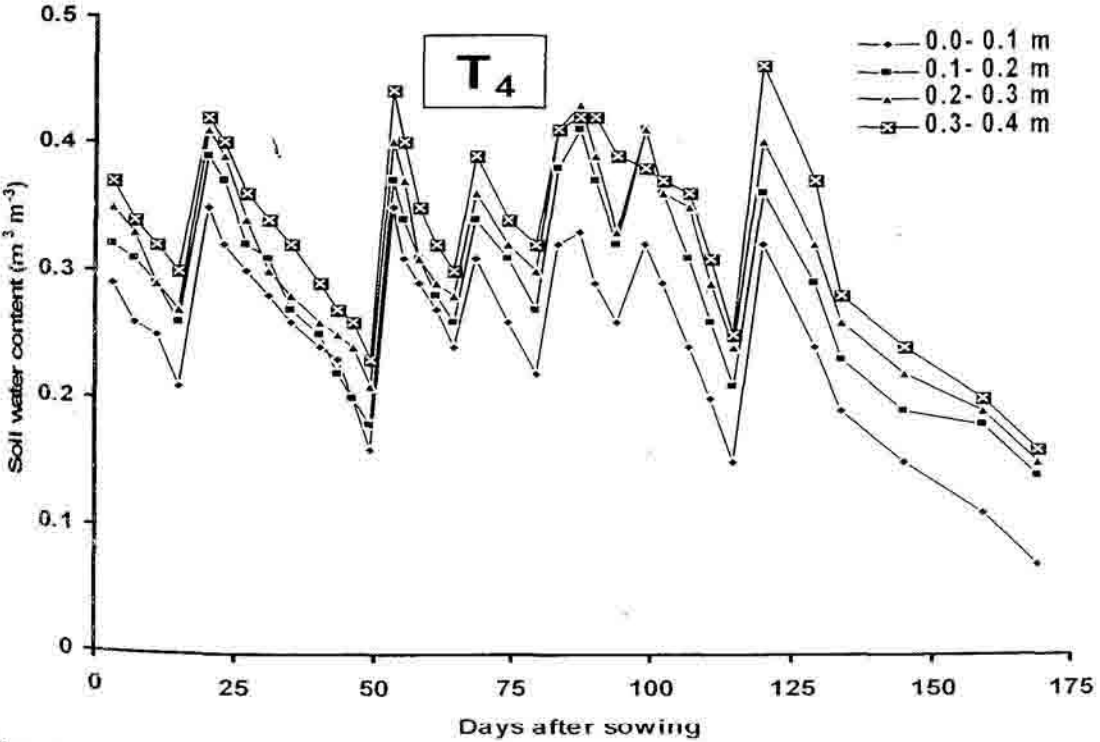


Figure 4.22: Changes in soil water content with time under tillage treatment T_4 at different depths (m) for the first wheat crop season (2002- 03)

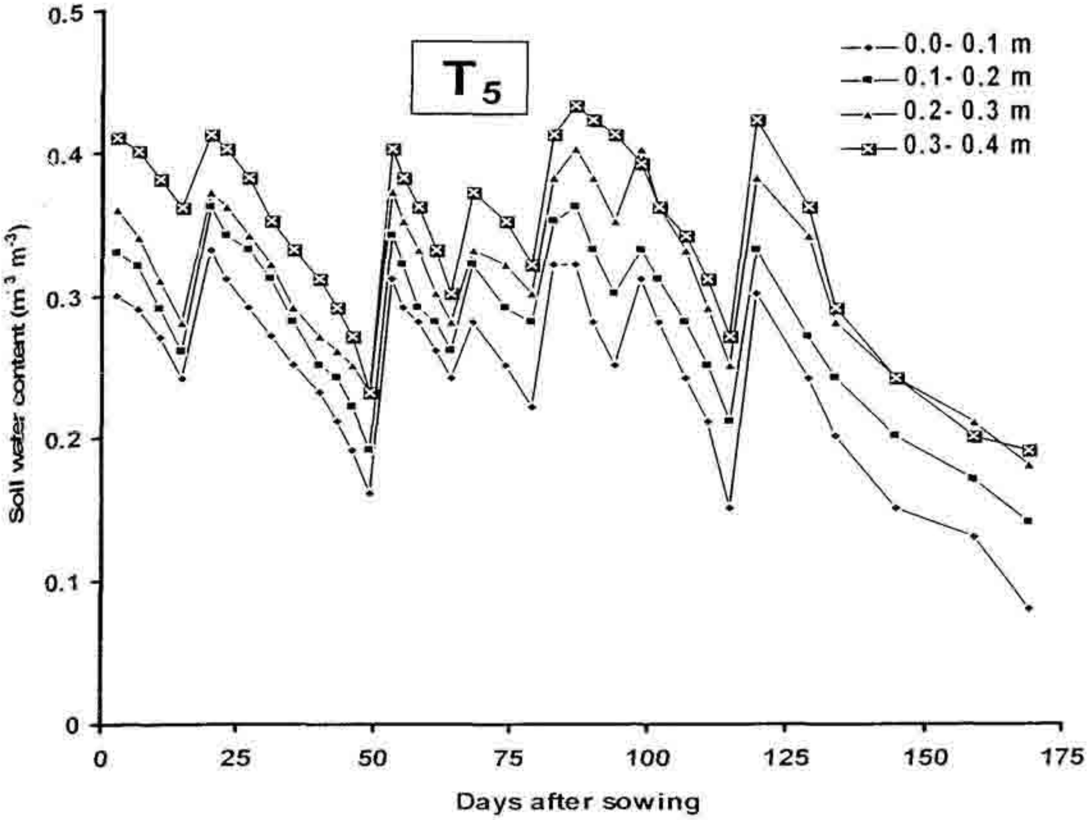


Figure 4.23: Changes in soil water content with time under tillage treatment T_5 at different depths (m) for the first wheat crop season (2002- 03)

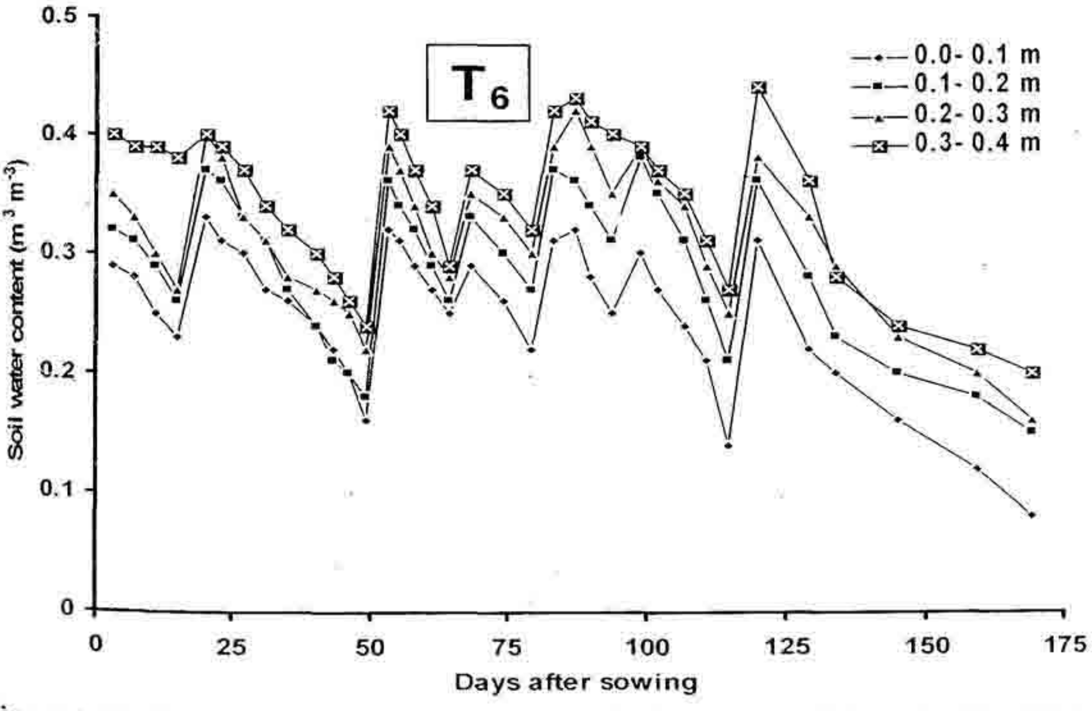


Figure 4.24: Changes in soil water content with time under tillage treatment T_6 at different depths (m) for the first wheat crop season (2002- 03)

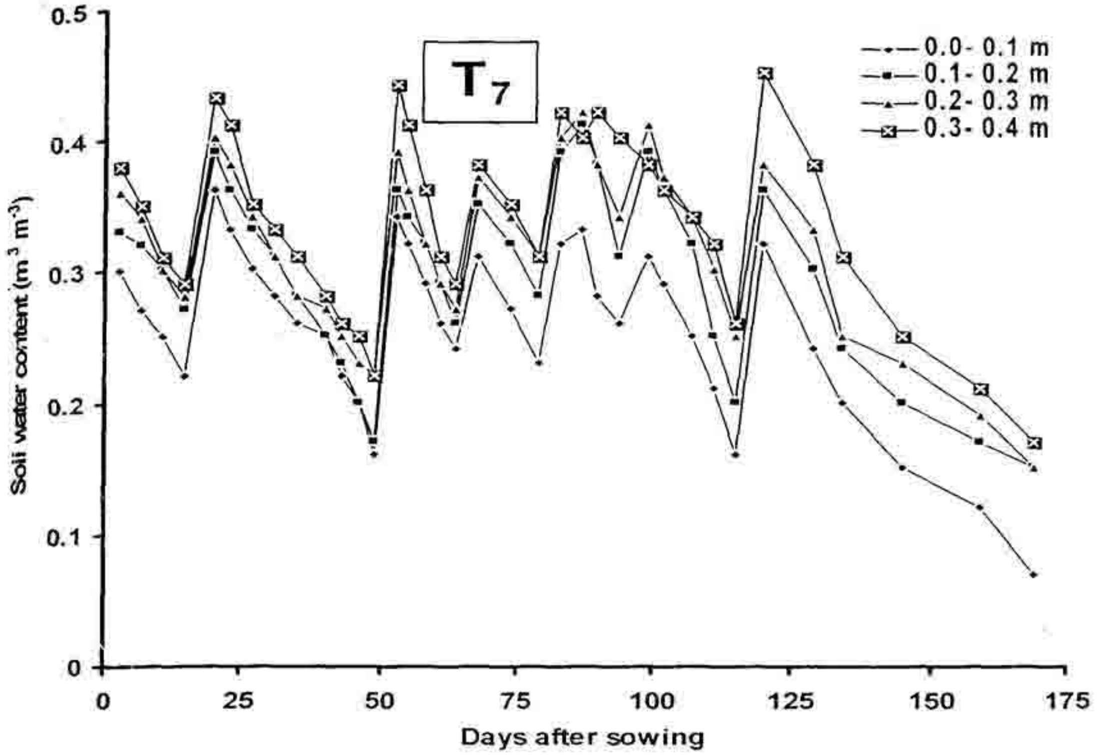


Figure 4.25: Changes in soil water content with time under tillage treatment T_7 at different depths (m) for the first wheat crop season (2002- 03)

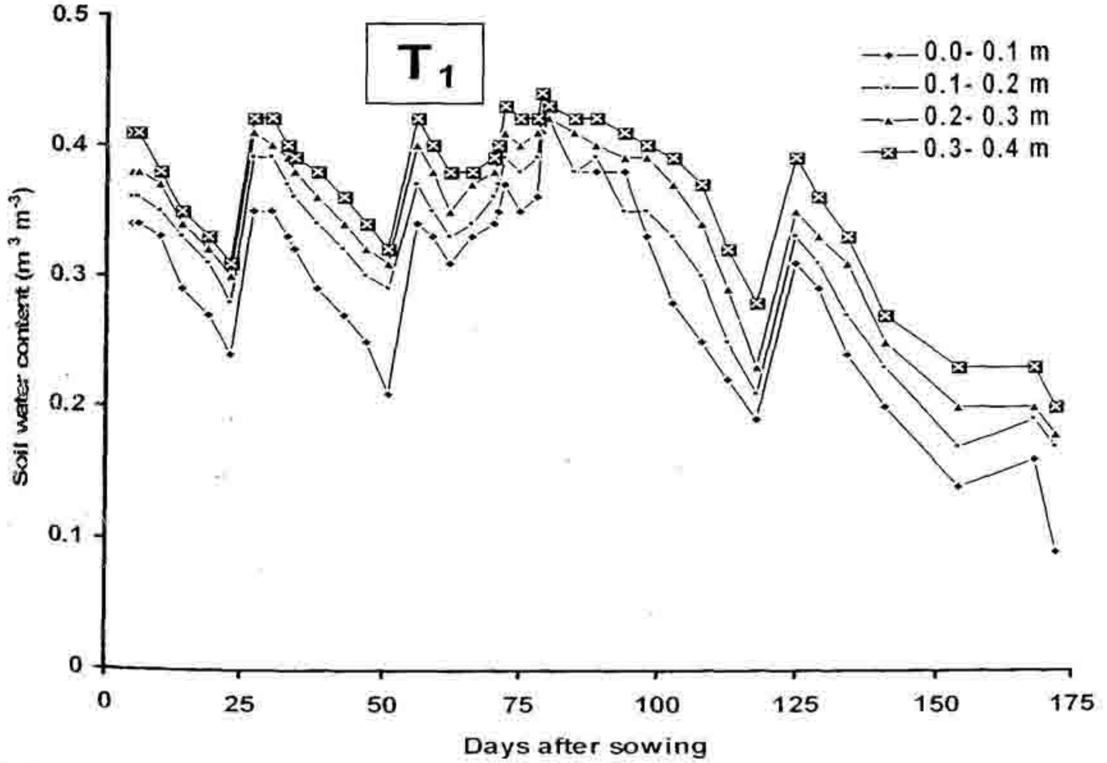


Figure 4.26: Changes in soil water content with time under tillage treatment T_1 at different depths (m) for the second wheat crop season (2003- 04)

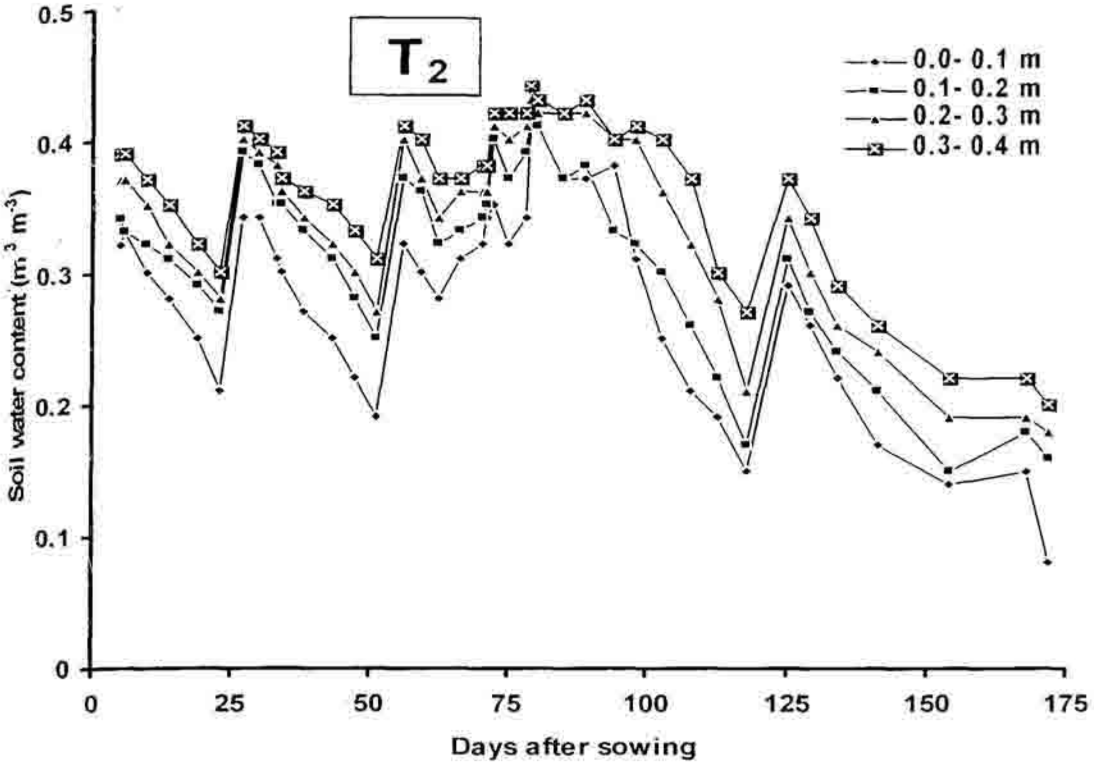


Figure 4.27: Changes in soil water content with time under tillage treatment T_2 at different depths (m) for the second wheat crop season (2003- 04)

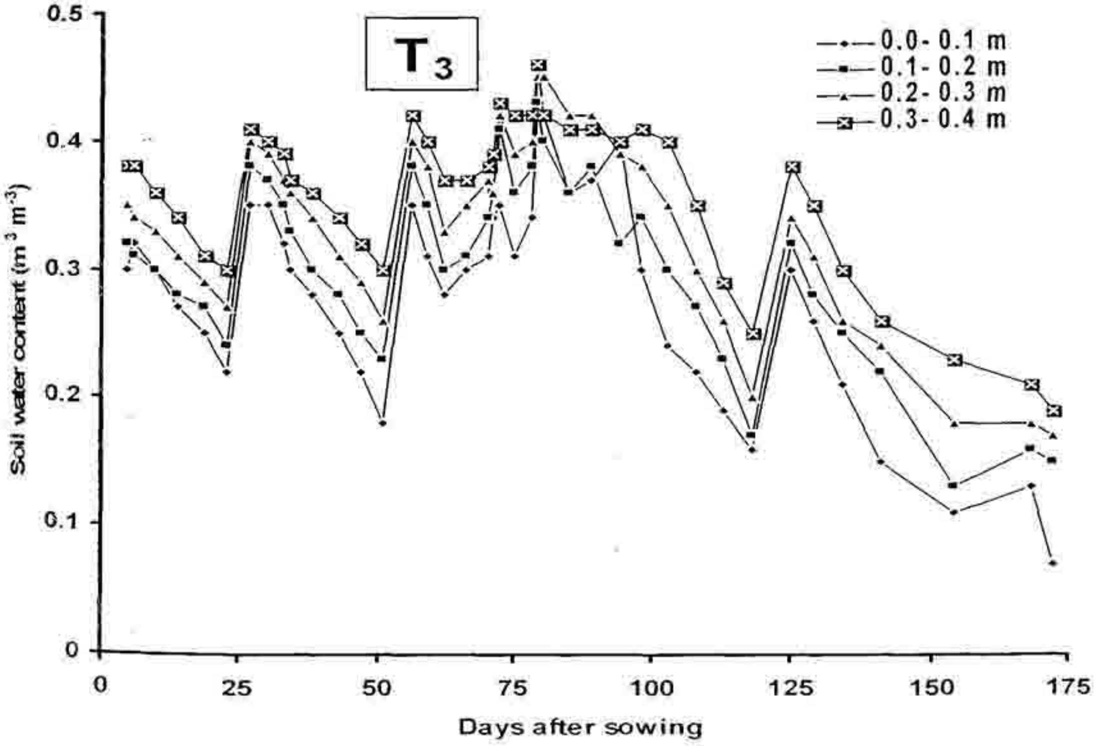


Figure 4.28: Changes in soil water content with time under tillage treatment T_3 at different depths (m) for second wheat crop season (2003- 04)

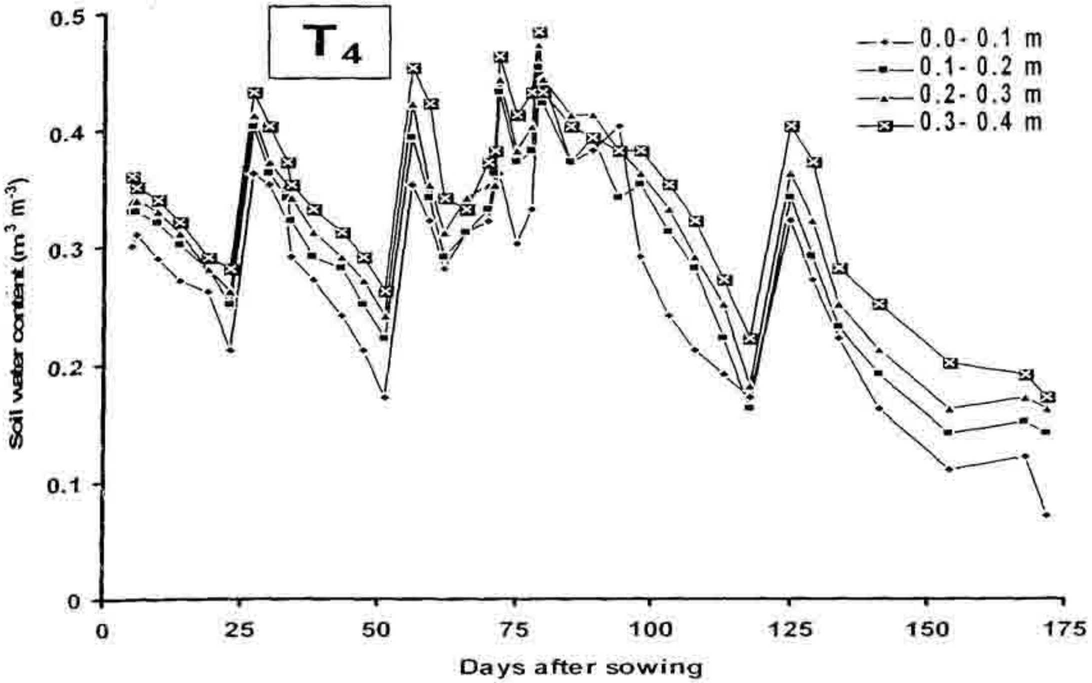


Figure 4.29: Changes in soil water content with time under tillage treatment T_4 at different depths (m) for the second wheat crop season (2003- 04)

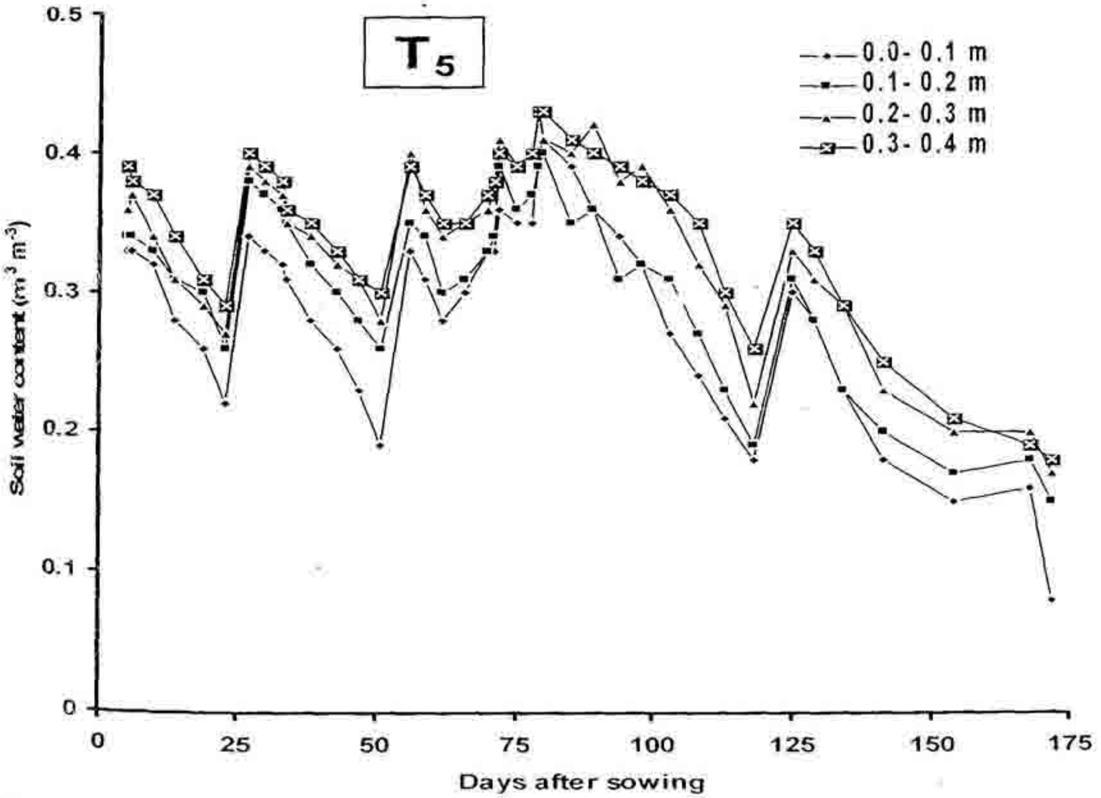


Figure 4.30: Changes in soil water content with time under tillage treatment T_5 at different depths (m) for the second wheat crop season (2003- 04)

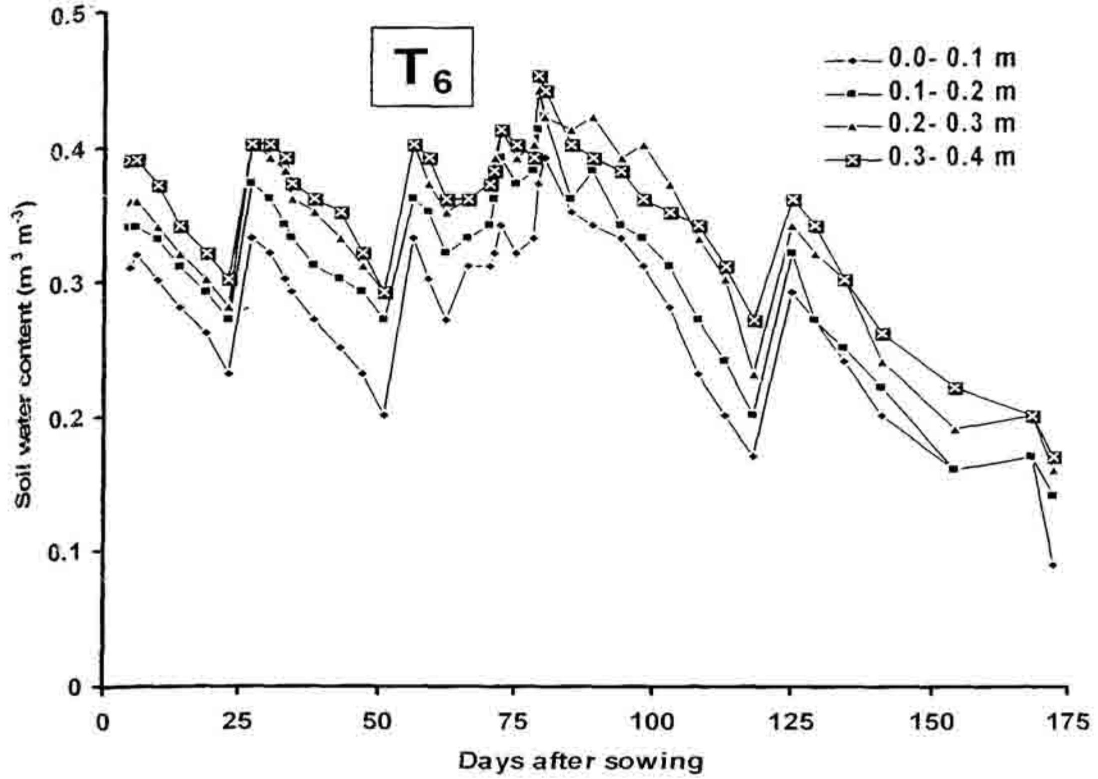


Figure 4.31: Changes in soil water content with time under tillage treatment T_6 at different depths (m) for the second wheat crop season (2003- 04)

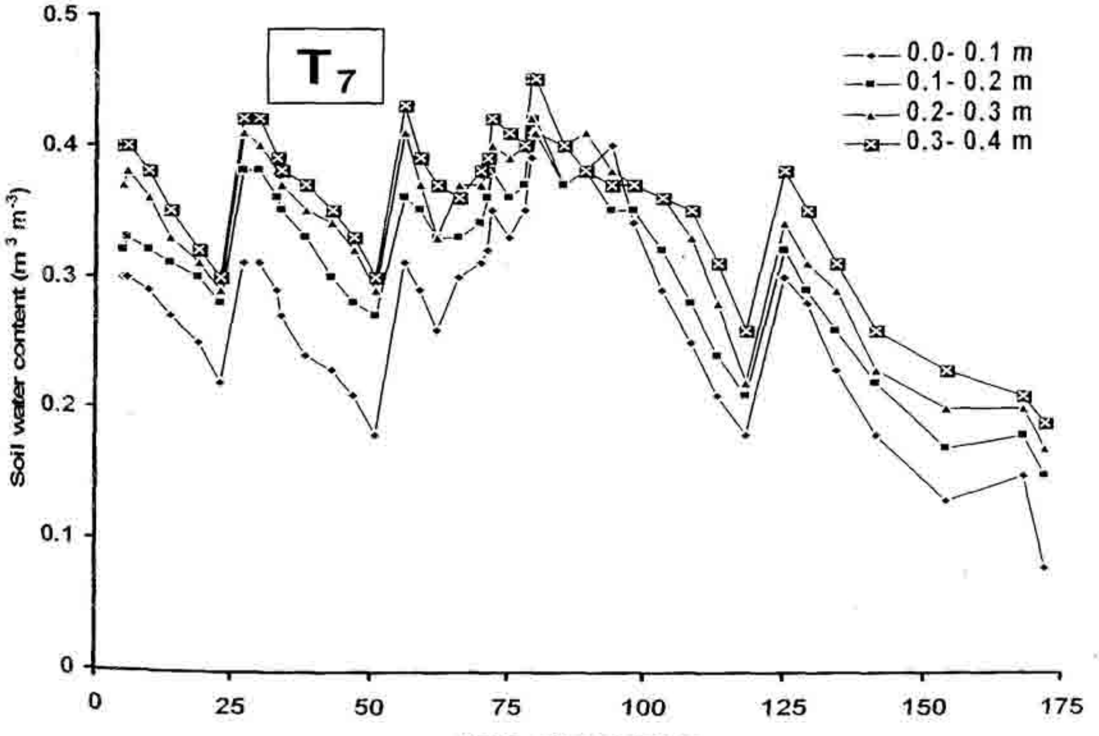


Figure 4.32: Changes in soil water content with time under tillage treatment T_7 at different depths (m) for the second wheat crop season (2003- 04)

4.3.2.2 Hydraulic conductivity

4.3.2.2.1 Saturated hydraulic conductivity

The depth-wise saturated hydraulic conductivity (k_s), determined at sowing and harvest in two wheat seasons (2002-03 and 2003-04) under different tillage treatments are presented in Figure 4.33, 4.34, 4.35 and 4.36. In both the years of study, treatment T_4 had significantly higher 'ks' values as compared to all the other tillage treatments at sowing and harvest of both wheat crops.

For the first year of the study, the 'k_s' values in 0.00-0.075 m soil depth at the time of sowing had significantly higher in treatment T_4 as compared to T_1, which remained statistically at par with T_2, T_3, T_5, T_6 and T_7 (Figure 4.33). Similarly, 'k_s' values for 0.075-0.15 m depth were significantly higher in treatment T_4 (statistically at par with T_7) as compared to T_1, T_2, T_3, T_5 and T_6, while in 0.15-0.30 m depth, T_1, T_2, T_3, T_5, T_6 and T_7 had lower 'k_s' as compared to T_4, respectively. At harvest of first wheat crop, 'k_s' values in all the three consecutive soil depths (0.00-0.075, 0.075-0.15 and 0.15-0.30 m soil depth) was statistically at par in treatments T_4 and T_7 but were significantly higher as compared to T_1, T_2, T_3, T_5 and T_6 (Figure 4.34), respectively.

The 'k_s' values at sowing during second year of the study were significantly higher in treatment T_4 (at par with T_3) as compared to T_1, T_2, T_5, T_6 and T_7 at 0.00-0.075 and 0.075-0.15 m soil depth. Similarly, T_4 had significantly higher 'k_s' values as compared to all the tillage treatments between 0.15 and 0.30 m soil depth (Figure 4.35). At second wheat crop sowing for 0.00-0.075 and

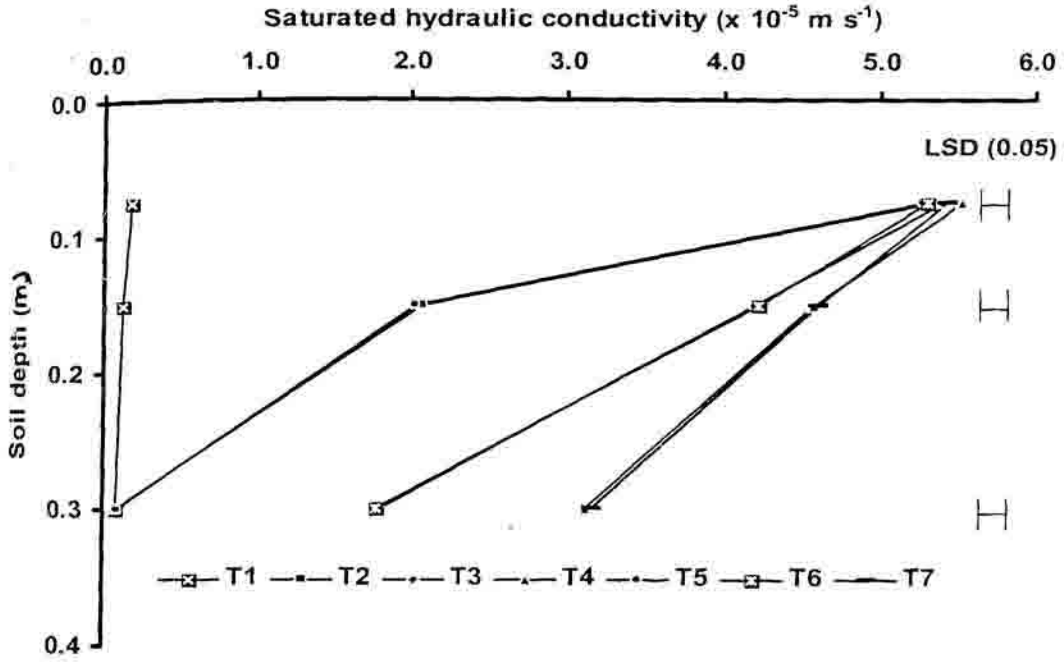


Figure 4.33: Depth-wise saturated hydraulic conductivity under different tillage treatments at the time of sowing of first wheat crop season (2002-03)

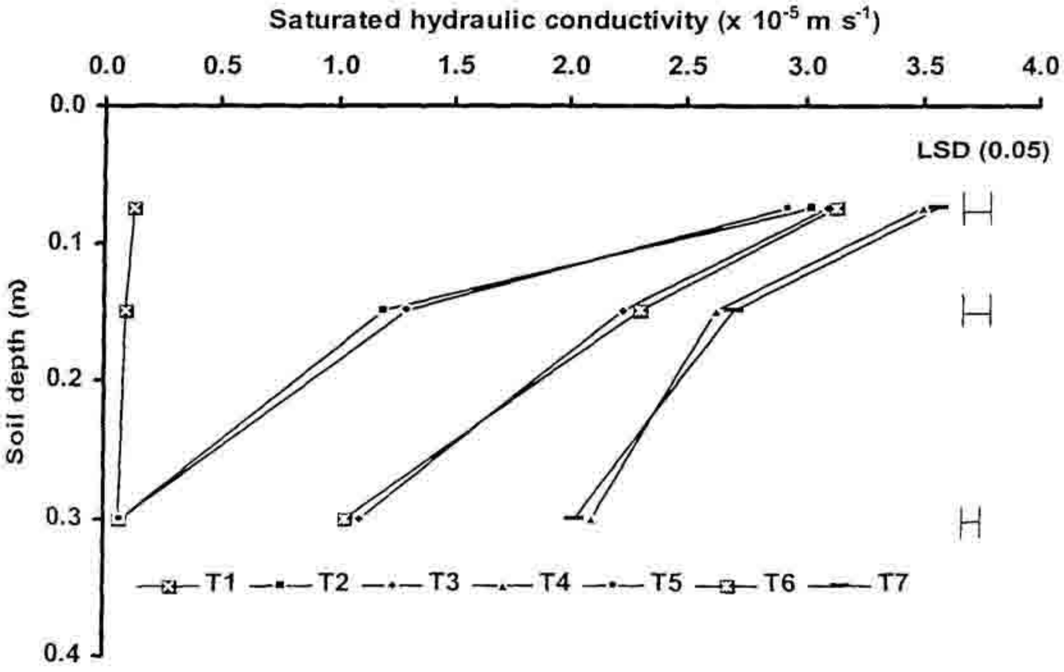


Figure 4.34: Depth-wise saturated hydraulic conductivity under different tillage treatments at the time of harvesting of first wheat crop season (2002- 03)

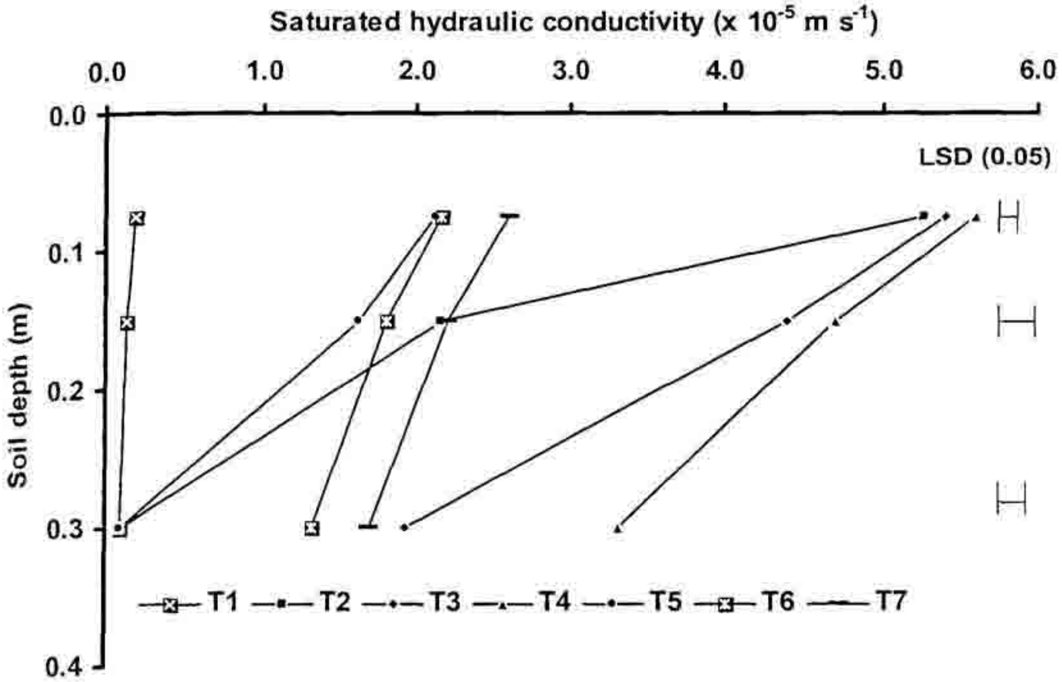


Figure 4.35: Depth-wise saturated hydraulic conductivity under different tillage treatments at the time of sowing of second wheat crop season (2003- 04)

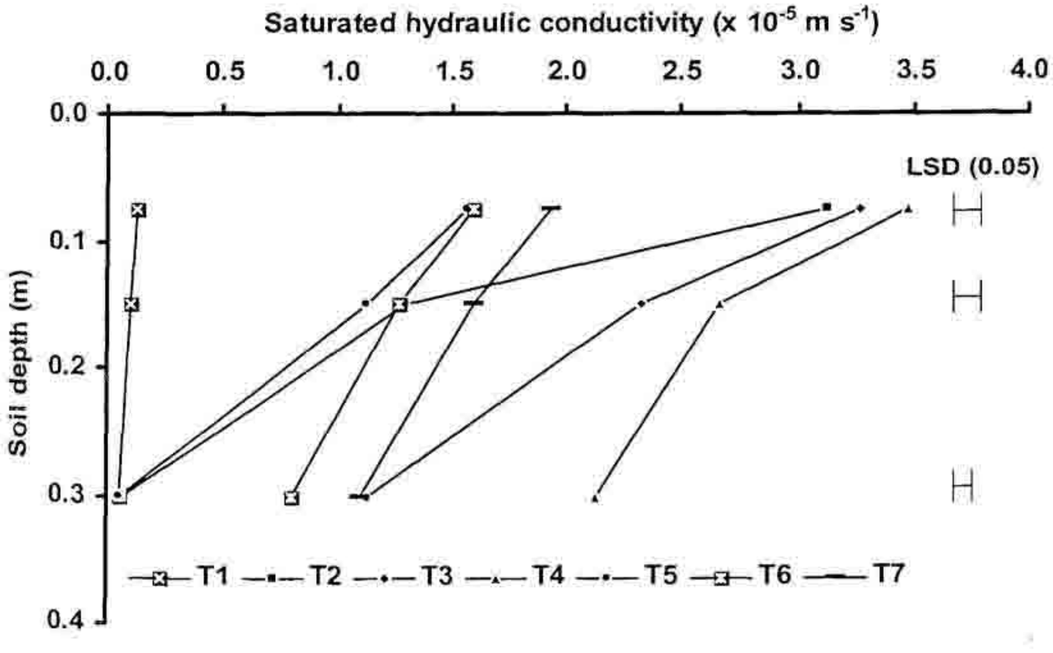


Figure 4.36: Depth-wise saturated hydraulic conductivity under different tillage treatments at the time of harvesting of second wheat crop season (2003- 04)

0.075-0.15 m soil depths, T_7 treatment had significantly higher 'k_s' values as compared to T_1, T_5 and T_6, however, between 0.15 and 0.30 m soil depth, T_1, T_2, T_5 and T_6, had lower 'k_s' values as compared to T_7. In all the three soil depths (0.00-0.075, 0.075-0.15 and 0.15-0.30 m), the 'k_s' values at harvest of crop were significantly higher in treatment T_4 as compared to T_1, T_2, T_3, T_5, T_6 and T_7. The next higher was T_7 which was significantly different from T_1, T_5 and T_6 (Figure 4.36).

4.3.2.2.2 Unsaturated hydraulic conductivity

The unsaturated hydraulic conductivity [$K(\theta)$] values obtained *in situ* for different layers are presented in Figure 4.37. In general, soil depths of 0.2-0.3 and 0.4-0.5 m showed higher values of $K(\theta)$ in comparison to the surface and intermediate layers of soil profile. The magnitude of difference between different layers in $K(\theta)$ increased with increase in water content. For example, at 20 per cent moisture content, the $K(\theta)$ values were 2.49×10^{-7}, 0.91×10^{-7}, 0.51×10^{-7}, 0.46×10^{-7} and 0.28×10^{-7} m s^{-1} for the soil depths of 0.2-0.3, 0.4-0.5, 0.3-0.4, 0.1-0.2 and 0.0-0.1 m, respectively, and at 60 per cent water content, the $K(\theta)$ values were 5.90×10^{-7}, 3.52×10^{-7}, 2.49×10^{-7}, 1.84×10^{-7} and 1.56×10^{-7} m s^{-1} for the depths of 0.2-0.3, 0.4-0.5, 0.3-0.4, 0.1-0.2 and 0.0-0.1 m, respectively.

4.3.2.3 Soil matric potential

The changes in matric potential (Ψ_m) with time in different tillage treatments at 0.1, 0.2, 0.3, 0.4 and 0.5 m depths during crop growth have been shown for two years of study period in Figure 4.38, 4.39, 4.40, 4.41, 4.43, 4.42 and 4.44 (2002-03) and Figure 4.45, 4.46, 4.47, 4.48, 4.49, 4.50 and 4.51 (2003-04),

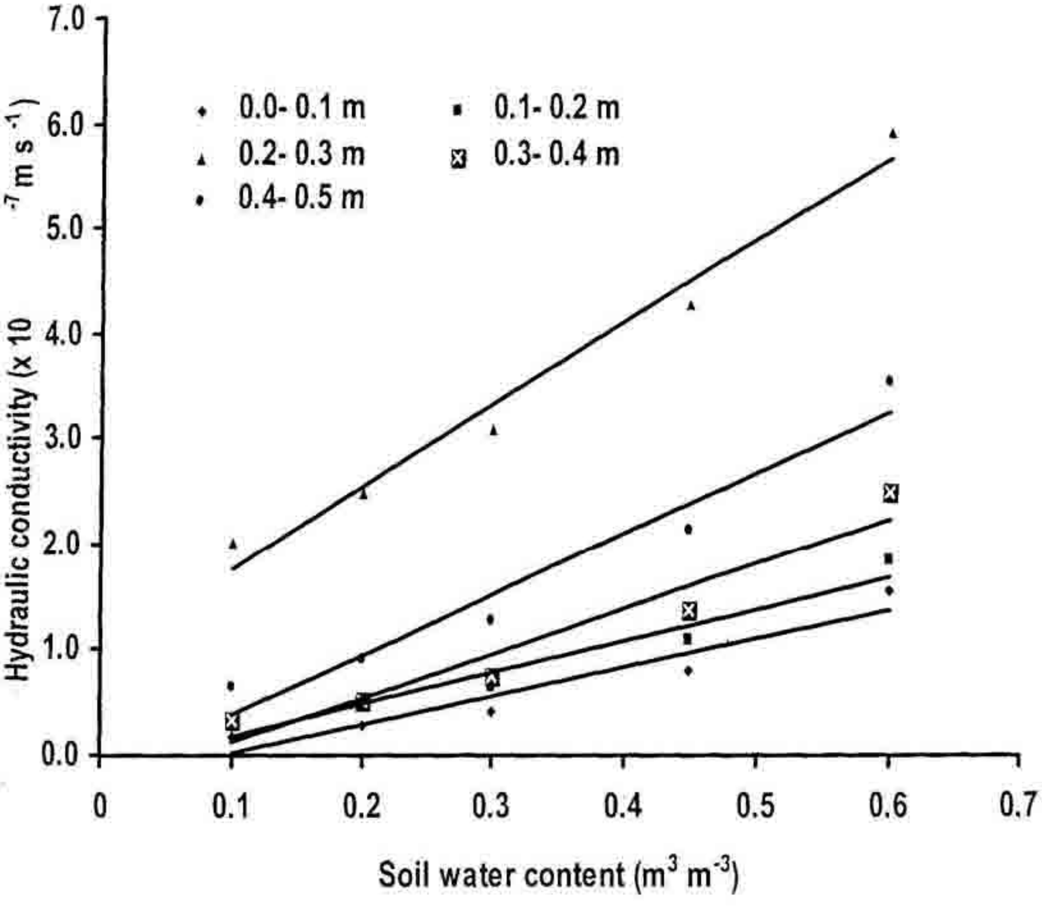


Figure 4.37: Field determined hydraulic conductivity values of the experimental site for wheat crop

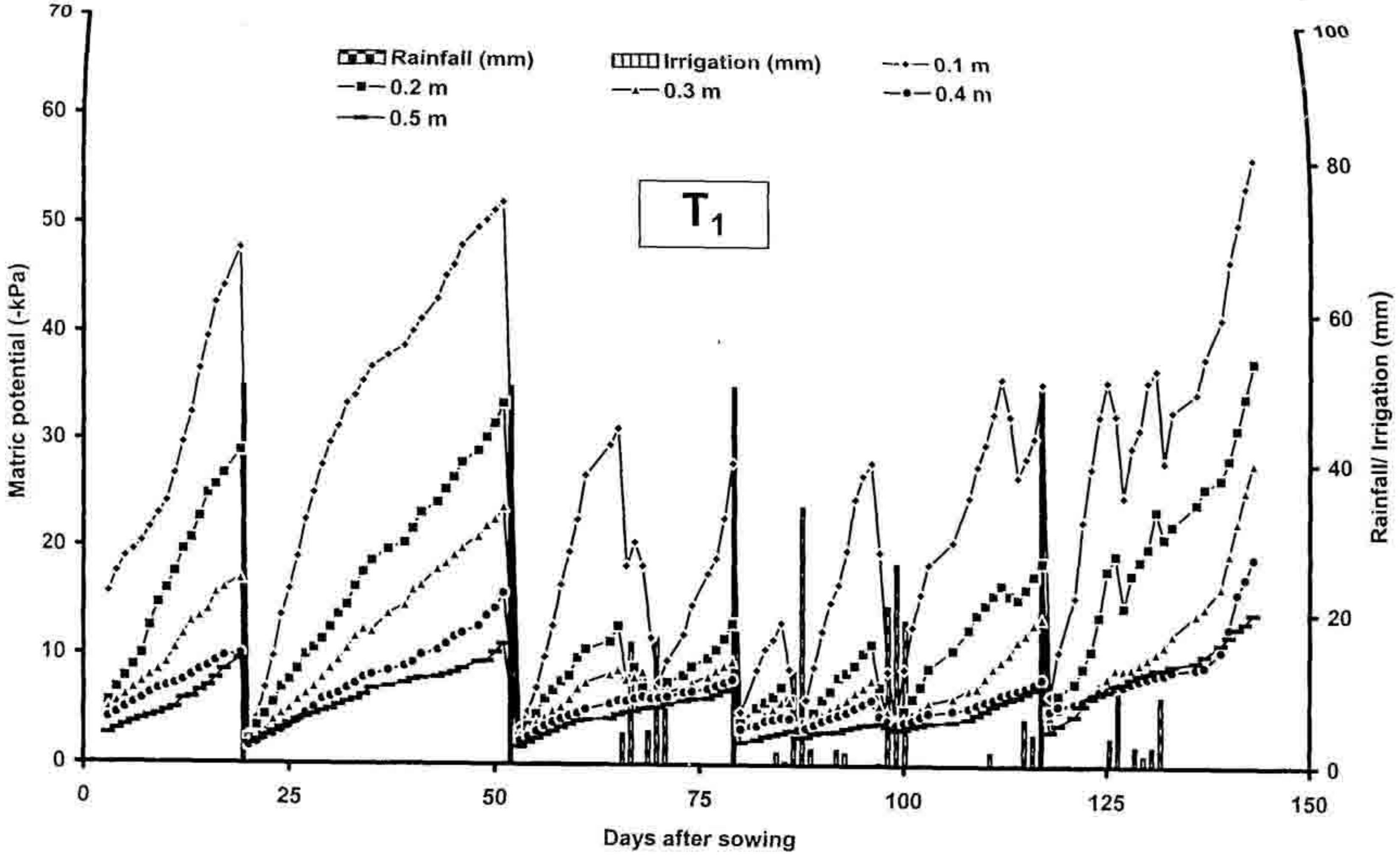


Figure 4.38: Changes in matric potential with time under tillage treatment T_1 at different depths (m) for the first wheat crop season (2002- 03)

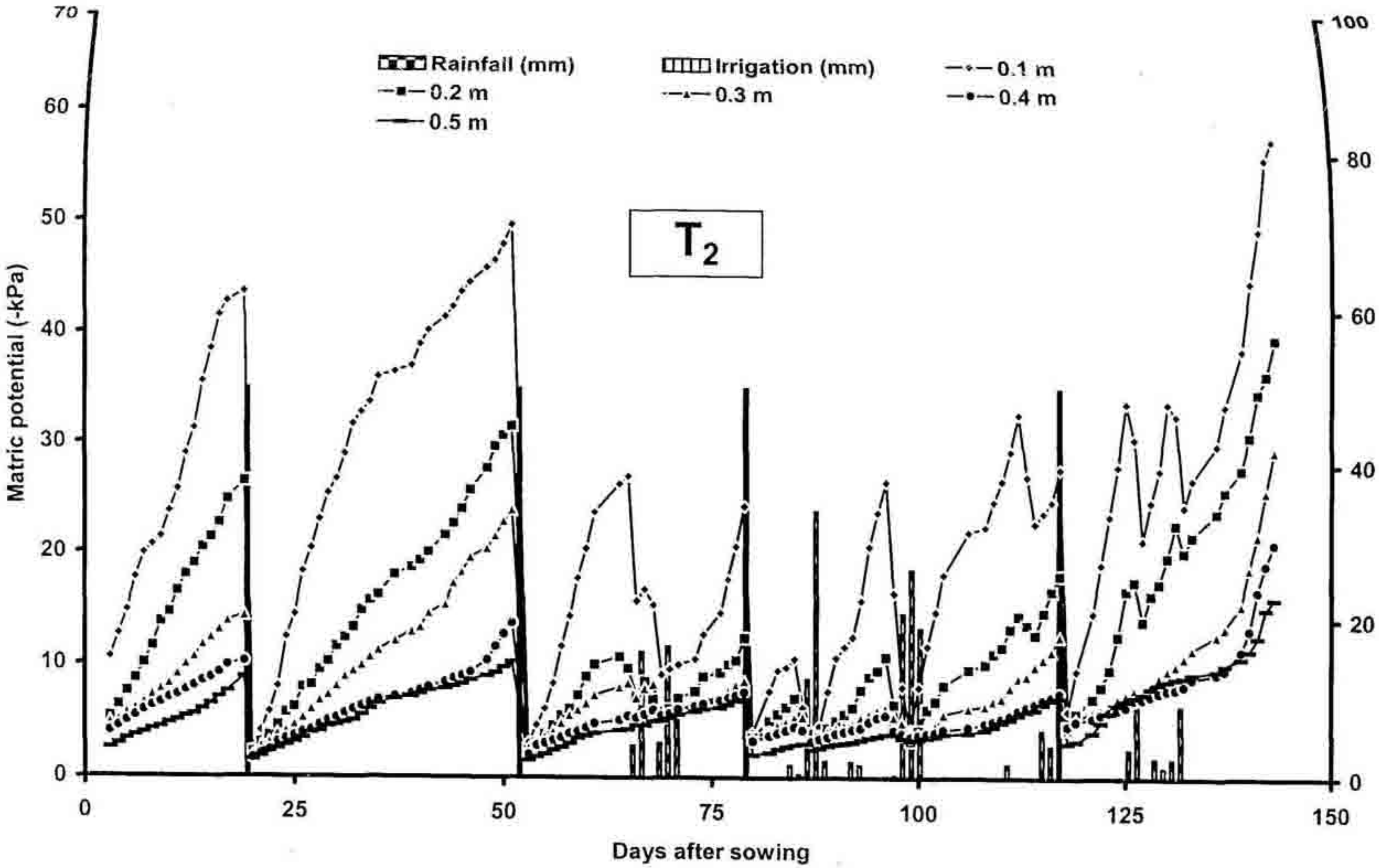


Figure 4.39: Changes in matric potential with time under tillage treatment T_2 at different depths (m) for the first wheat crop season (2002- 03)

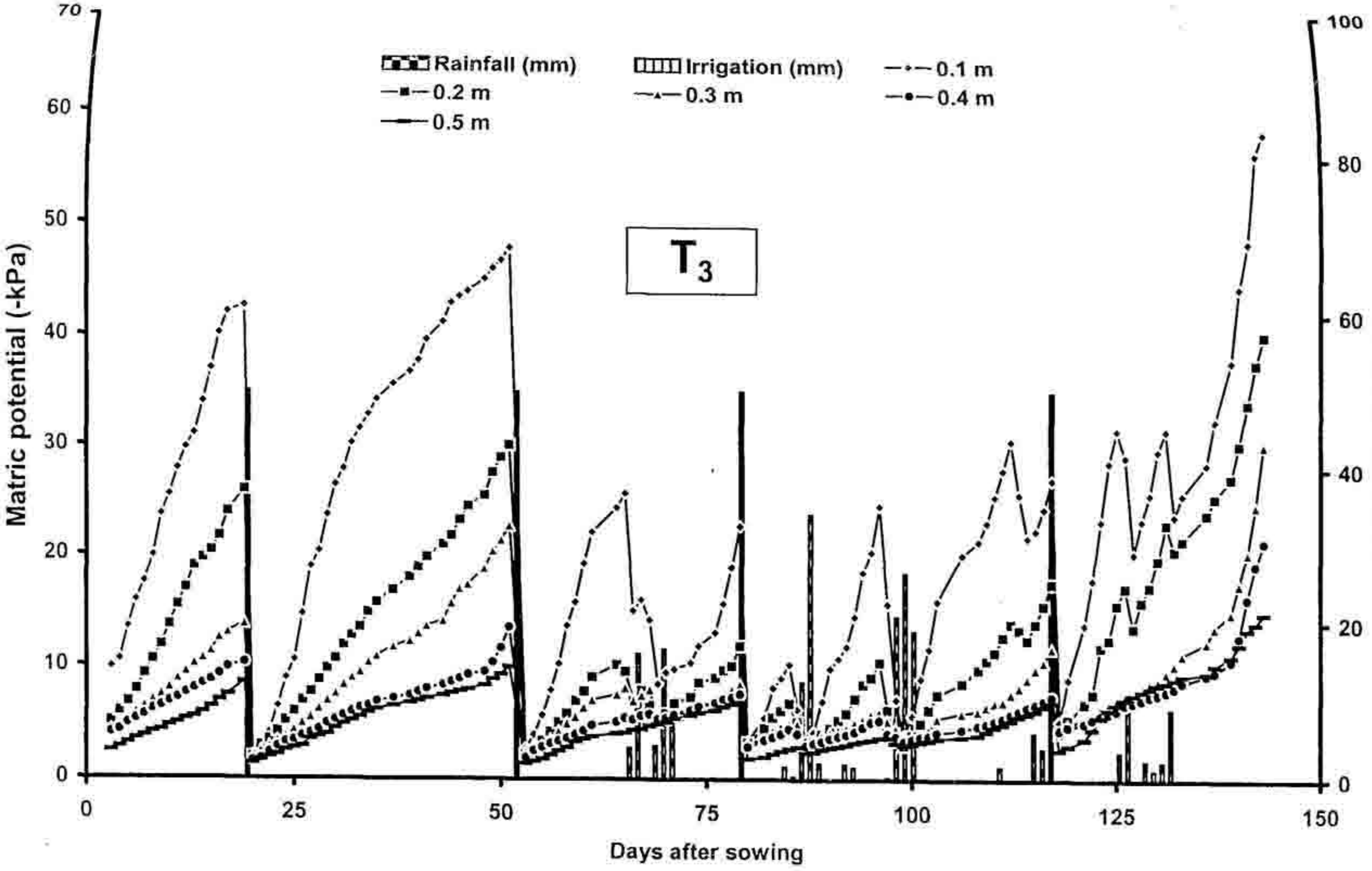


Figure 4.40: Changes in matric potential with time under tillage treatment T_3 at different depths (m) for the first wheat crop season (2002- 03)

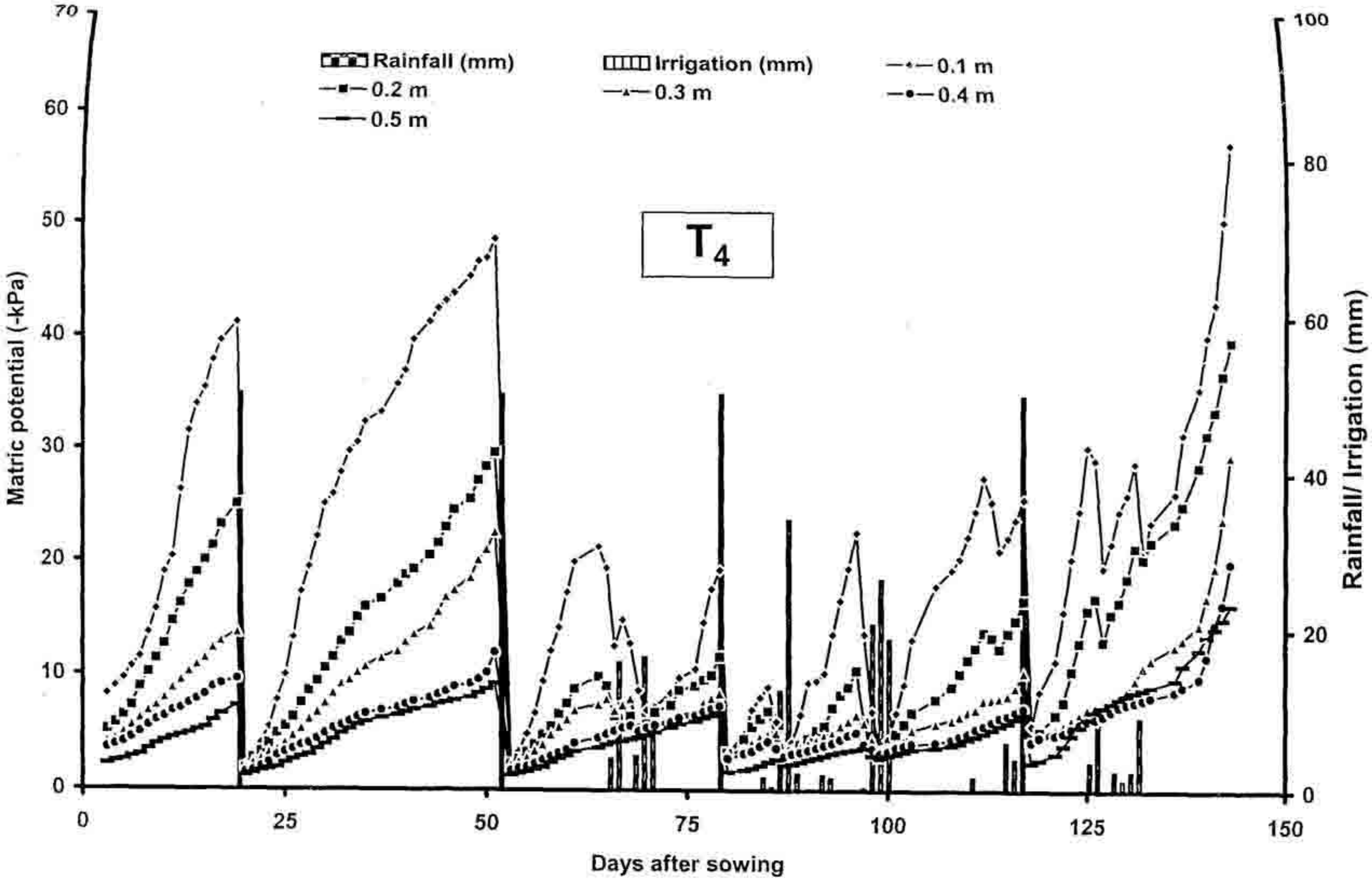


Figure 4.41: Changes in matric potential with time under tillage treatment T_4 at different depths (m) for the first wheat crop season (2002- 03)

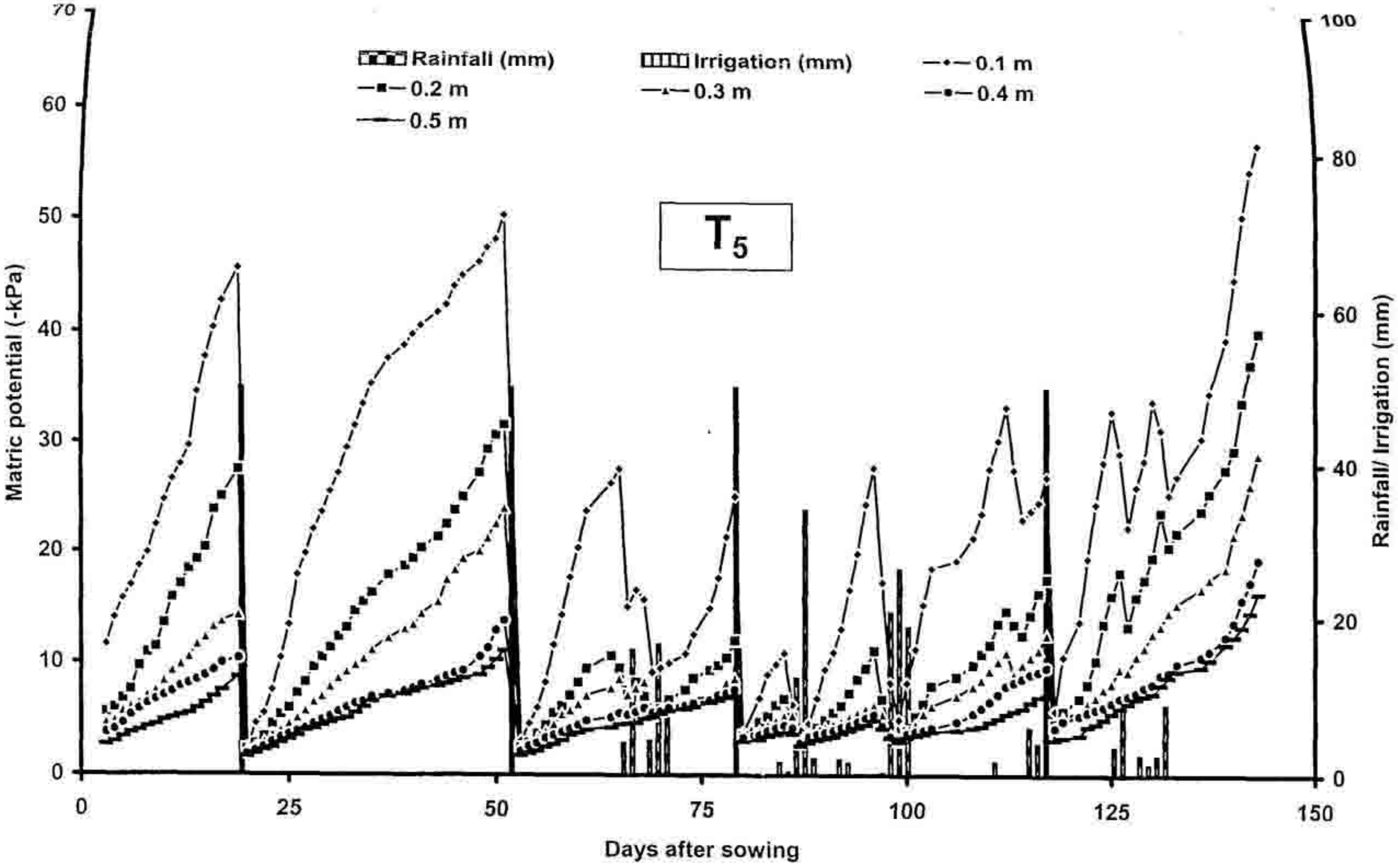


Figure 4.42: Changes in matric potential with time under tillage treatment T_5 at different depths (m) for the first wheat crop season (2002- 03)

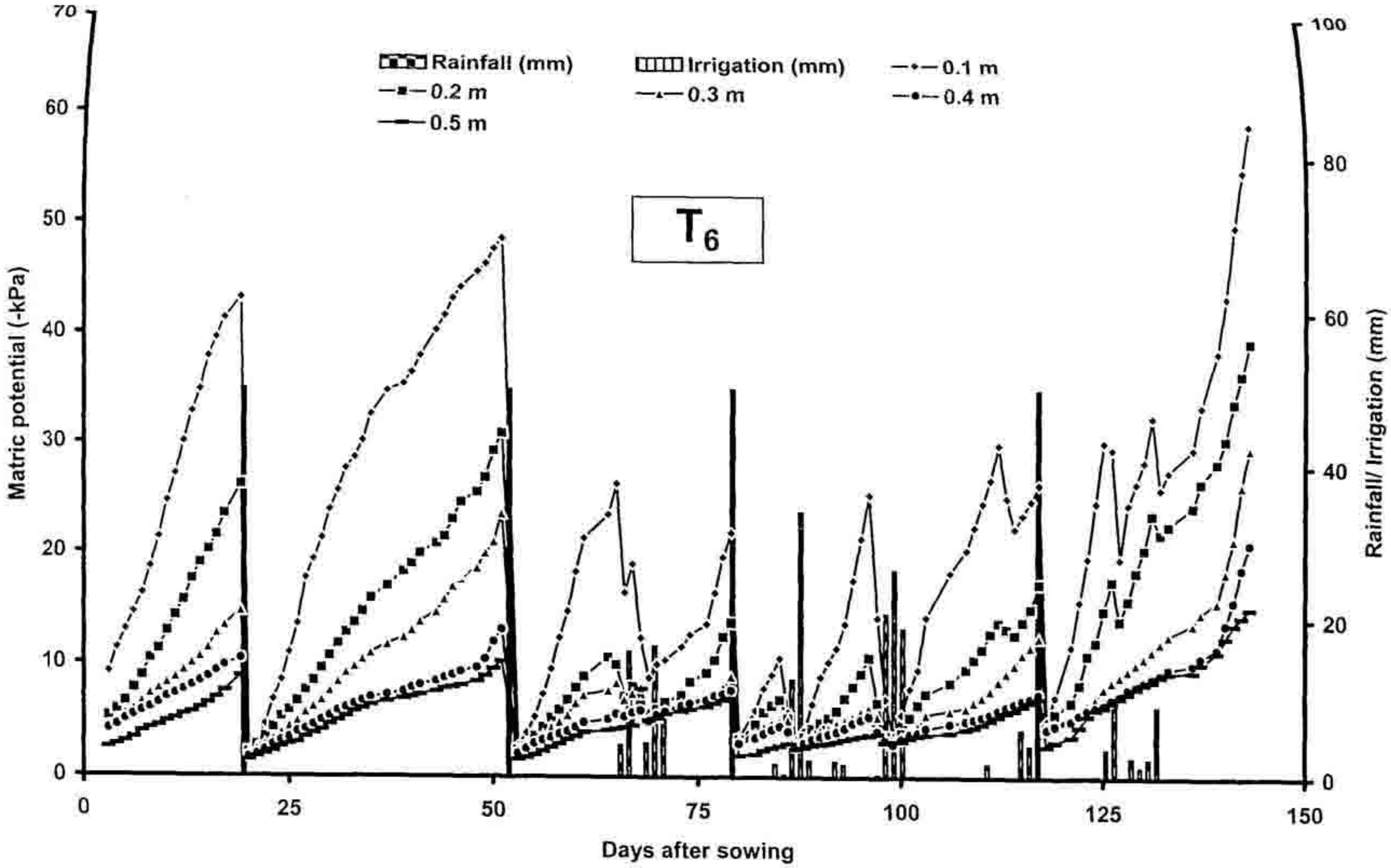


Figure 4.43: Changes in matric potential with time under tillage treatment T_6 at different depths (m) for the first wheat crop season (2002- 03)

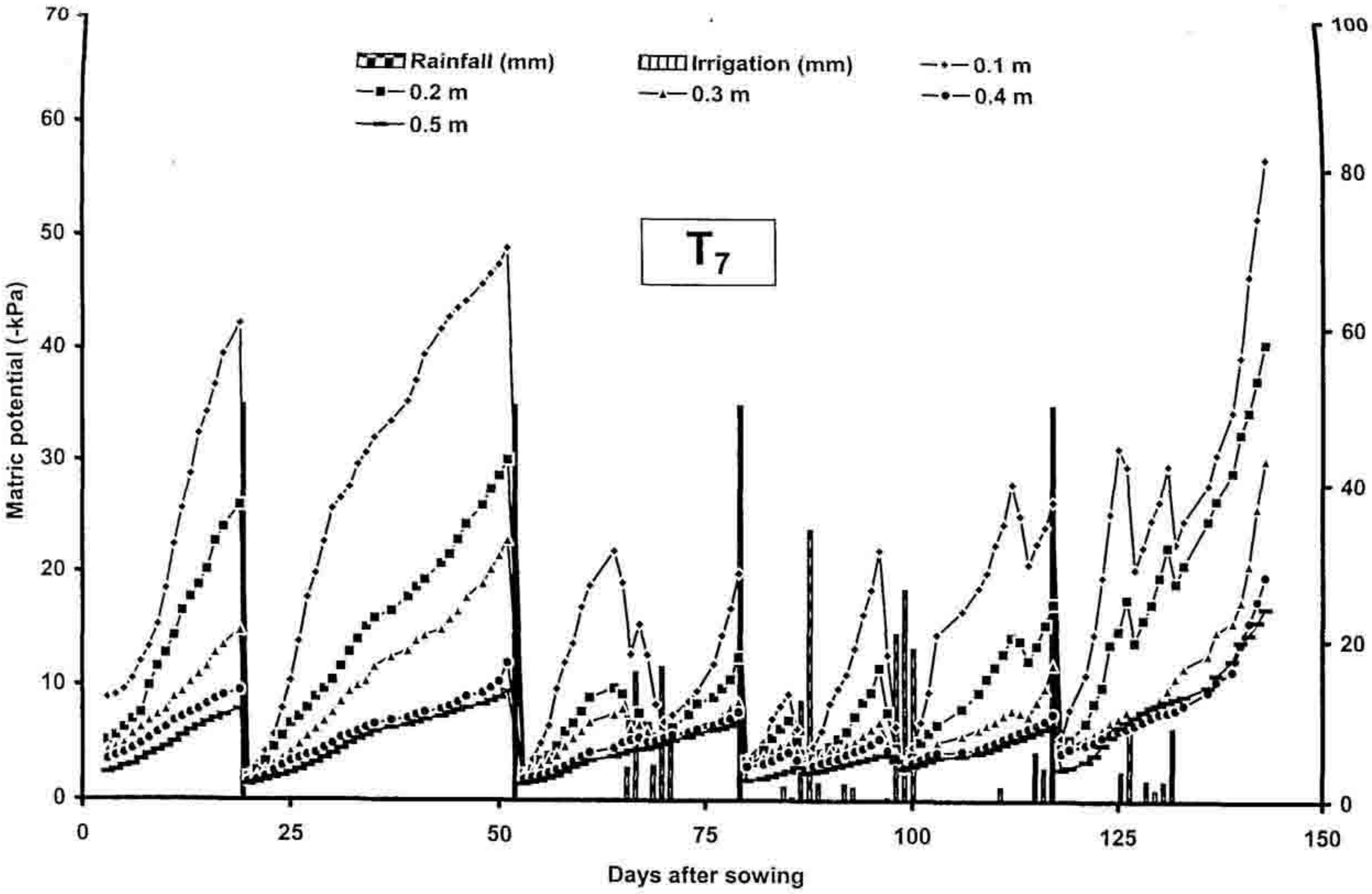


Figure 4.44: Changes in matric potential with time under tillage treatment T_7 at different depths (m) for the first wheat crop season (2002- 03)

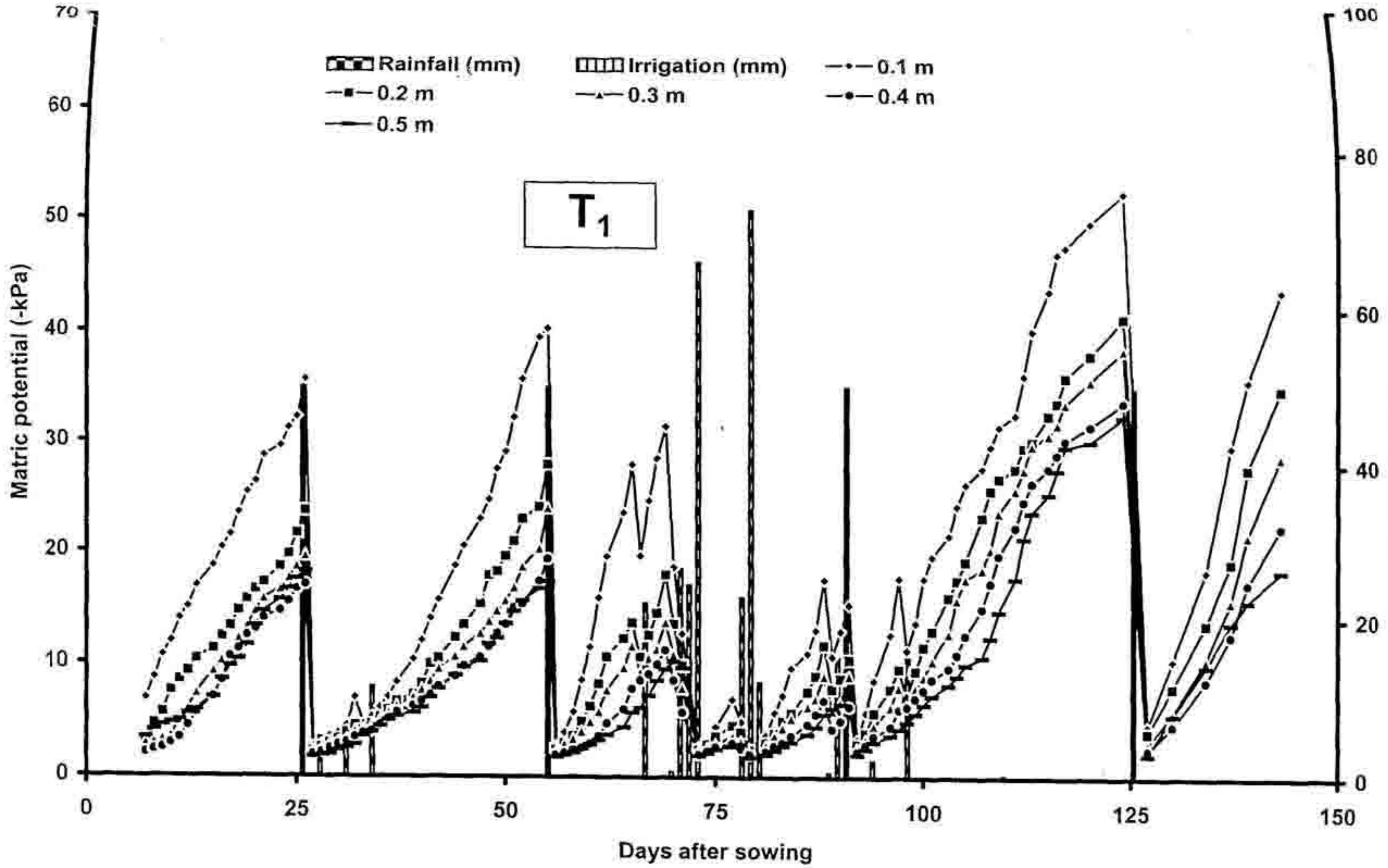


Figure 4.45: Changes in matric potential with time under tillage treatment T_1 at different depths (m) for the second wheat crop season (2003- 04)

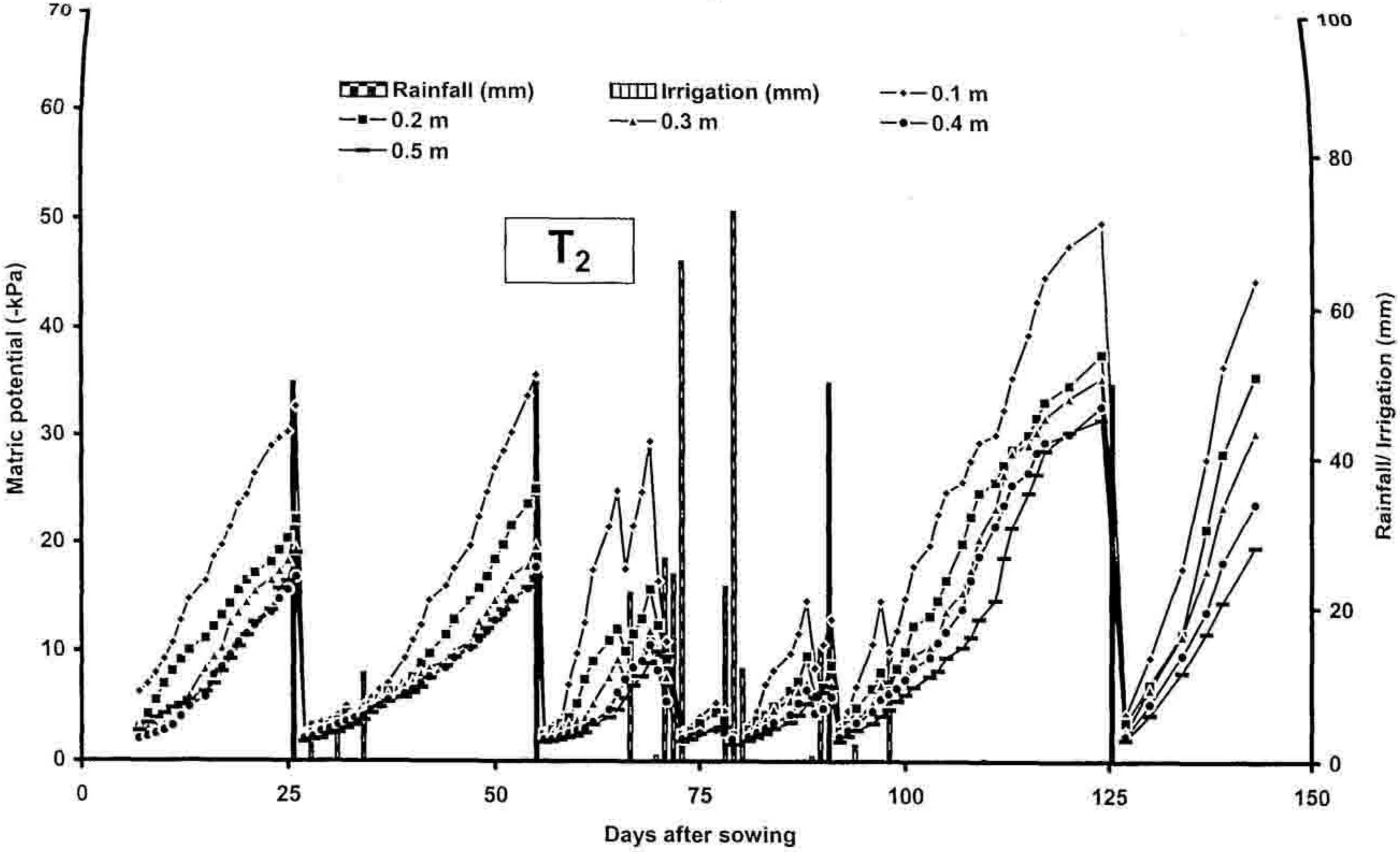


Figure 4.46: Changes in matric potential with time under tillage treatment T_2 at different depths (m) for the second wheat crop season (2003- 04)

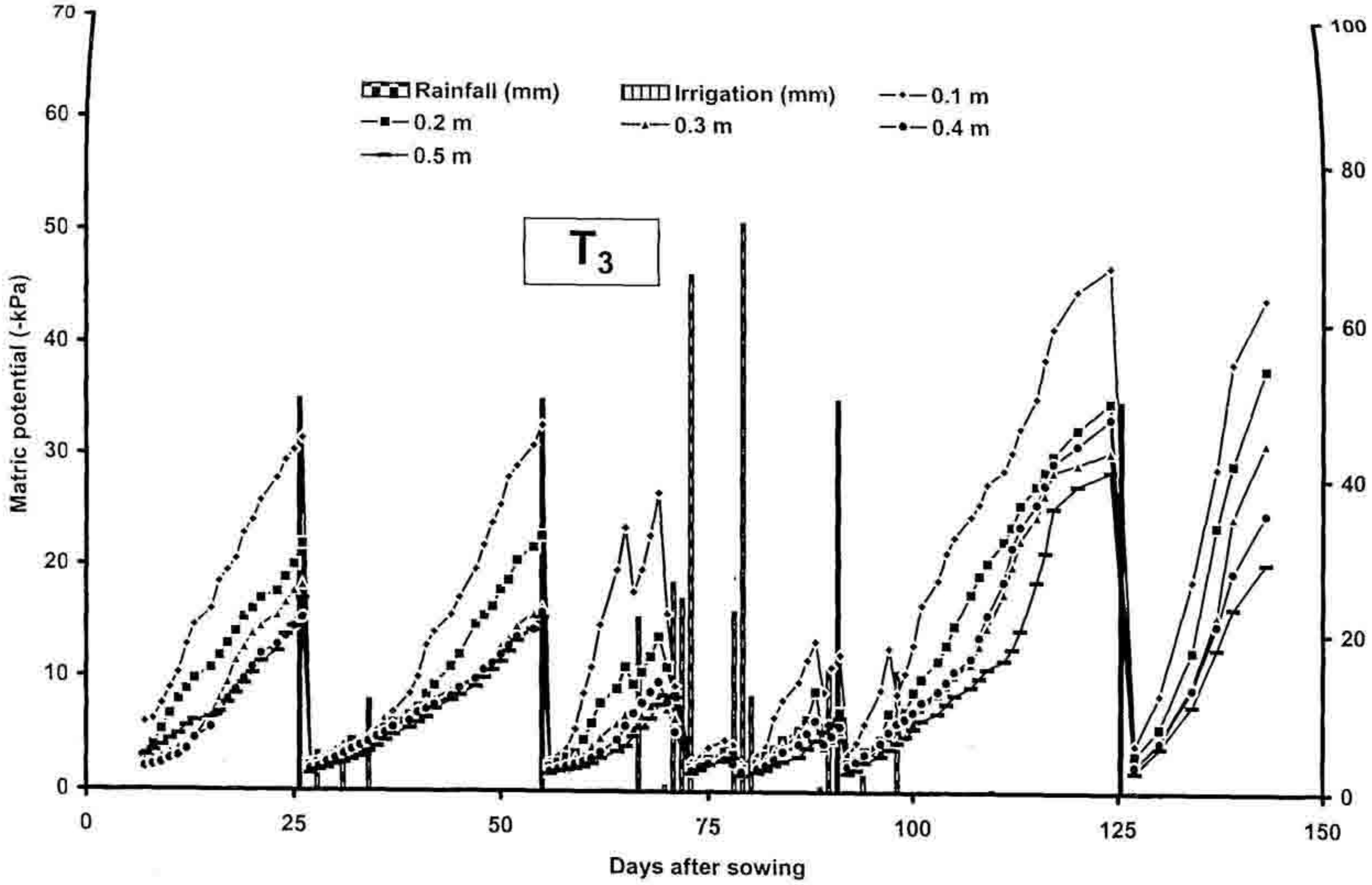


Figure 4.47: Changes in matric potential with time under tillage treatment T_3 at different depths (m) for the second wheat crop season (2003- 04)

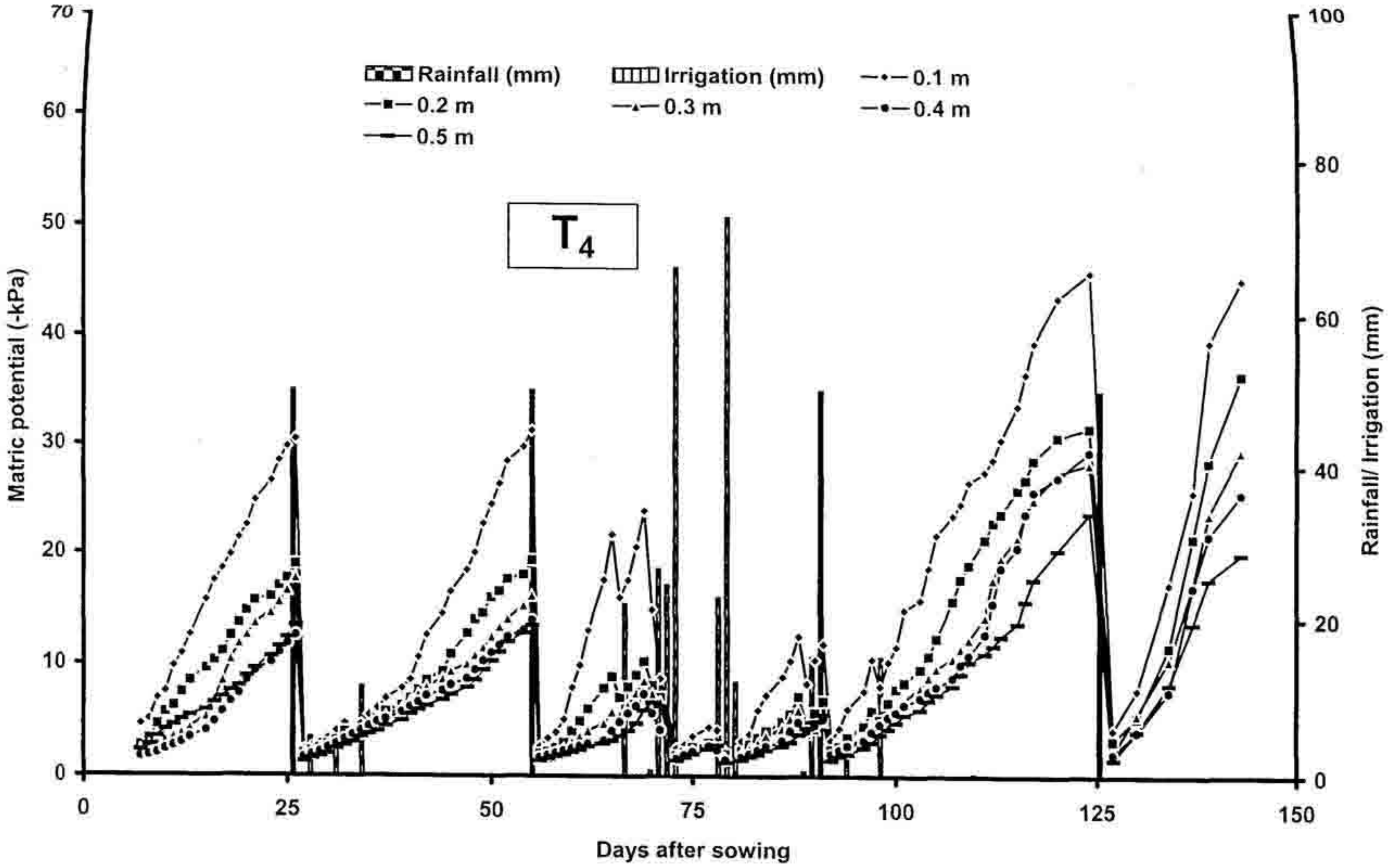


Figure 4.48: Changes in matric potential with time under tillage treatment T_4 at different depths (m) for the second wheat crop season (2003- 04)

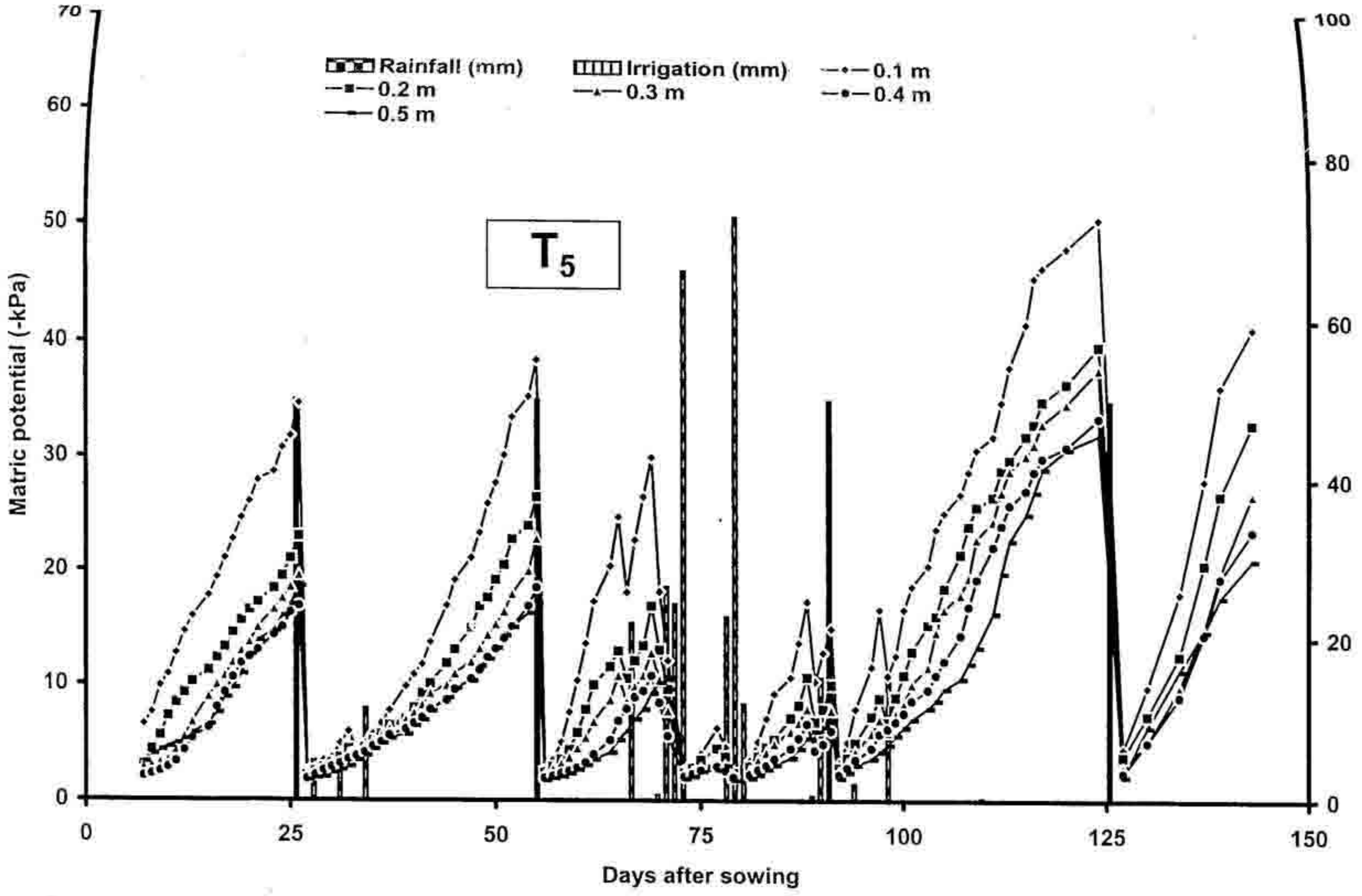


Figure 4.49: Changes in matric potential with time undertillage treatment T_5 at different depths (m) for the second wheat crop season (2003- 04)

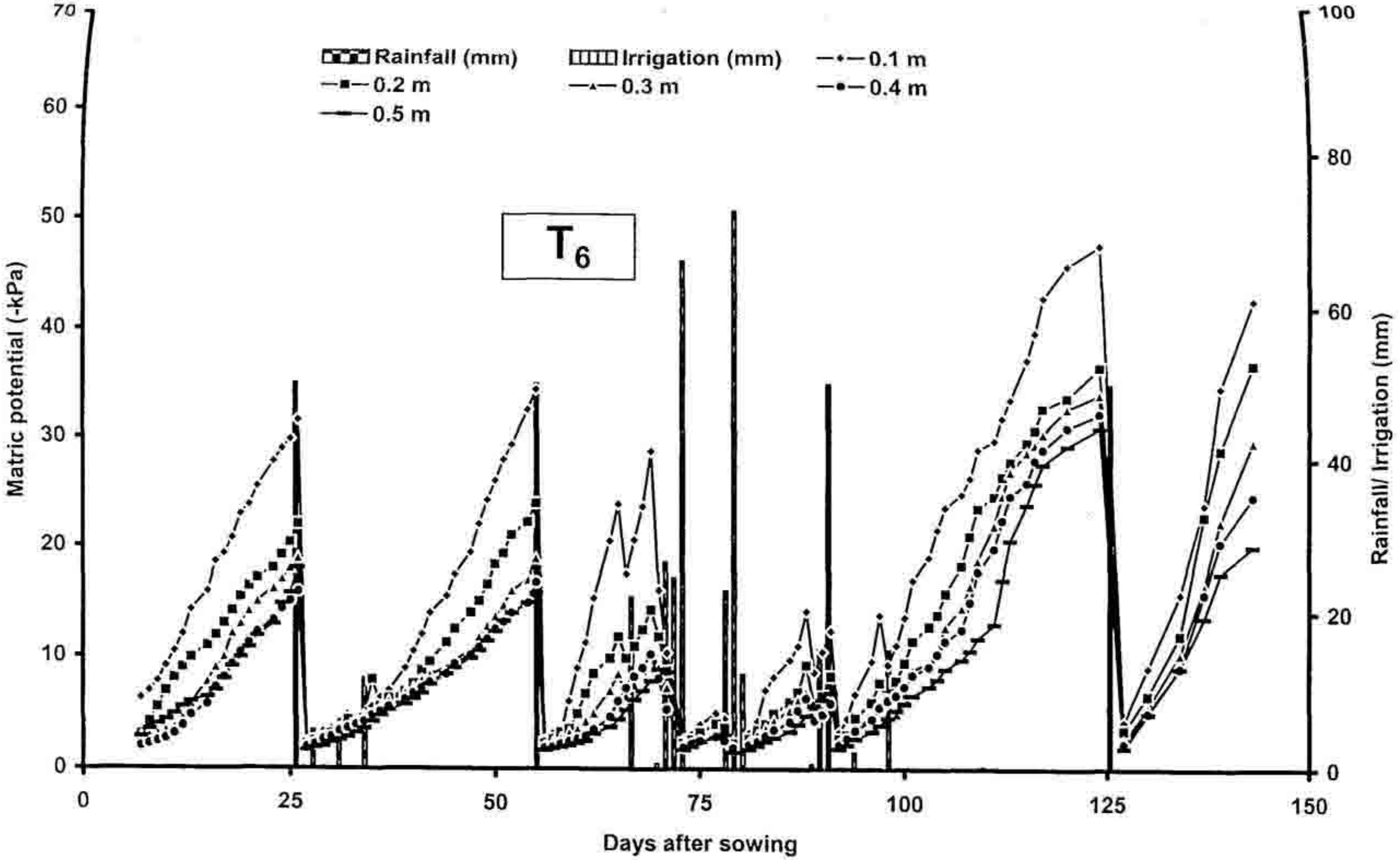


Figure 4.50: Changes in matric potential with time under tillage treatment T_6 at different depths (m) for the second wheat crop season (2003- 04)

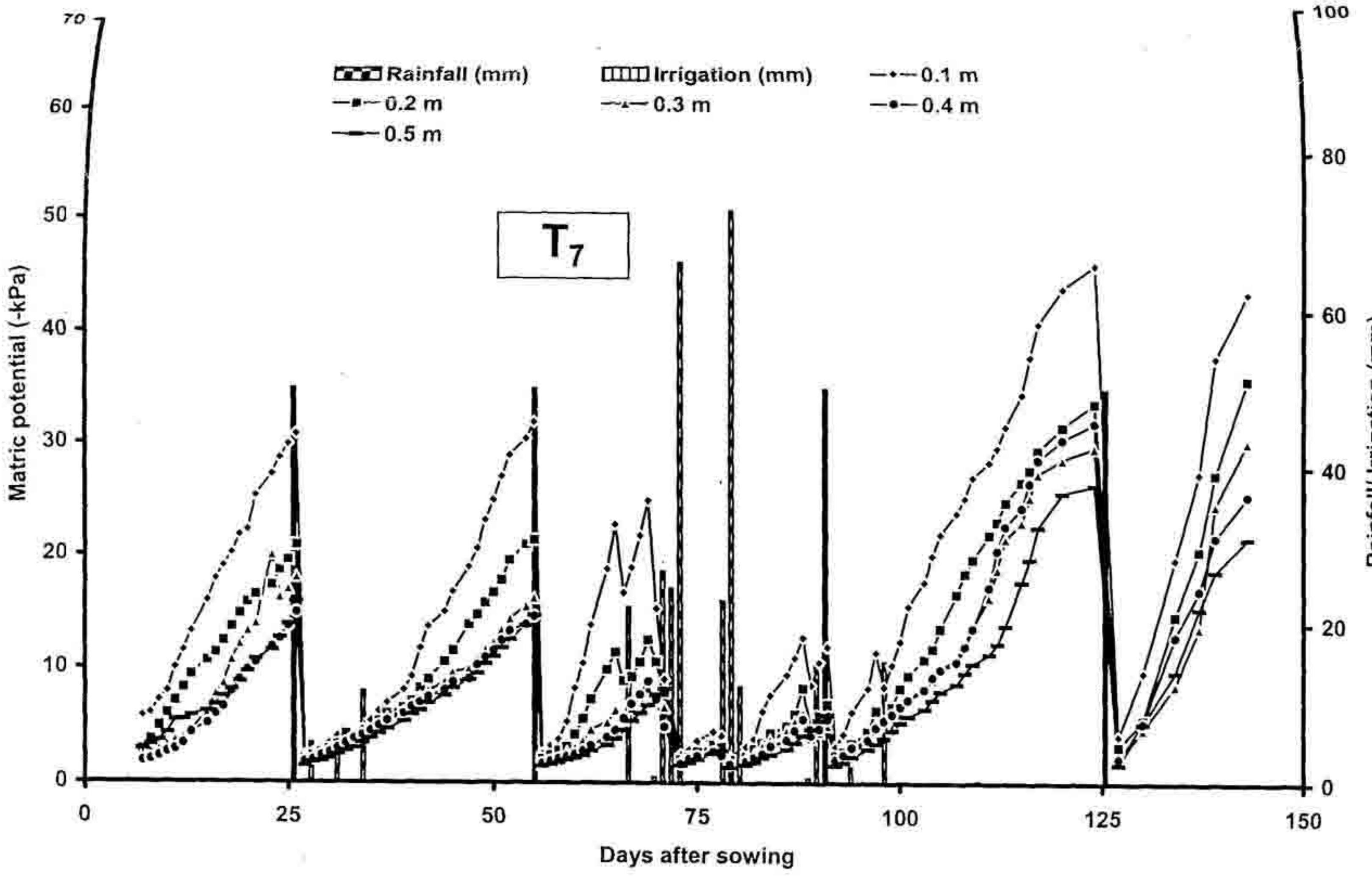


Figure 4.51: Changes in matric potential with time under tillage treatment T_7 at different depths (m) for the second wheat crop season (2003- 04)

respectively. The 'Ψ_m' values increased with depth of soil. In no tillage treatment (T_1), 'Ψ_m' values in 0.0-0.1 and 0.1-0.2 m soil depth were decreased in general as the dry period progressed. In general, whenever there was a rainfall event, the 'Ψ_m' values increased immediately in the upper 0.0-0.1 m layer but increased gradually in the lower layers.

During first year of the wheat crop season (2002-03), the 'Ψ_m' values at 20 DAS were higher in T_4 as compared to T_1, T_2, T_3, T_5, T_6 and T_7 treatments for 0.1, 0.2, 0.3, 0.4 and 0.5 m depths when first irrigation of 5 cm was applied one day before. However, when there were rainless periods, the 'Ψ_m' values were lower in T_1 as compared to T_2, T_3, T_4, T_5, T_6 and T_7 in all the depths. On 87 DAS (34.0 mm rainfall), the 'Ψ_m' values for 0.1, 0.2, 0.3, 0.4 and 0.5 m depths were higher in T_4 and T_7 as compared to T_1, T_2, T_3, T_5 and T_6 (Figure 4.38, 4.39, 4.40, 4.41, 4.43, 4.42 and 4.44).

During the second year of the study (2002-03), the 'Ψ_m' values at 27 DAS were higher in T_4 as compared to T_1, T_2, T_3, T_5, T_6 and T_7 treatments when first irrigation of 5 cm was applied one day before. Further, the 'Ψ_m' values were higher in T_1 as compared to T_2, T_3, T_4, T_5, T_6 and T_7 in all the soil depths when there were rainless periods. On 79 DAS (72.5 mm rainfall), the 'Ψ_m' values for 0.1, 0.2, 0.3, 0.4 and 0.5 m depths were higher in T_4 as compared to T_1, T_2, T_3, T_5, T_6 and T_7 (Figure 4.45, 4.46, 4.47, 4.48, 4.49, 4.50 and 4.51).

4.3.2.4 Hydraulic gradients

The changes in hydraulic gradient with time in different tillage treatments at 0.1-0.2, 0.2-0.3, 0.3-0.4 and 0.4-0.5 m depths during crop growth period have been shown for two years of study period in Figure 4.52, 4.53, 4.54, 4.55, 4.56. 4.57 and 4.58 (2002-03) and Figure 4.59, 4.60, 4.61, 4.62, 4.63, 4.64 and 4.65 (2003-04), respectively. At a glance, these figures revealed that during both the years of the study, the movement of water was mostly upward. The magnitude of upward movement was highest for the 0.0-0.3 m layer as compared to all the other depths. The 0.4-0.5 m depth had the least upward movement and some downward movement was also observed for this layer. In almost all the treatments, the hydraulic gradients at soil depths of 0.3-0.4 and 0.4-0.5 m remains almost around the line of zero flux. Periods beyond 125 days, registered downward movement noticed in 0.4-0.5 m depth.

4.3.2.5 Hydraulic flux

The changes in hydraulic flux with time in different tillage treatments at 0.1-0.2, 0.2-0.3, 0.3-0.4 and 0.4-0.5 m depths during crop growth period have been shown for two years of study period in Figure 4.66, 4.67, 4.68, 4.69, 4.70, 4.71 and 4.72 (2002-03) and Figure 4.73, 4.74, 4.75, 4.76, 4.77, 4.78 and 4.79 (2003-04), respectively. In general, in all the treatments for the both year the upward hydraulic flux were noticed. Magnitude of the upward hydraulic flux varied among different soil depths. The layer of 0.2-0.3 m had the maximum hydraulic flux while the lowest value was observed in 0.1-0.2 m depth in almost all the treatments. Downward flux was noticed in 0.2-0.3 m soil depth in almost all the treatments (0.0-0.05 m day^{-1}) at 60, 100 and 125-140 days after

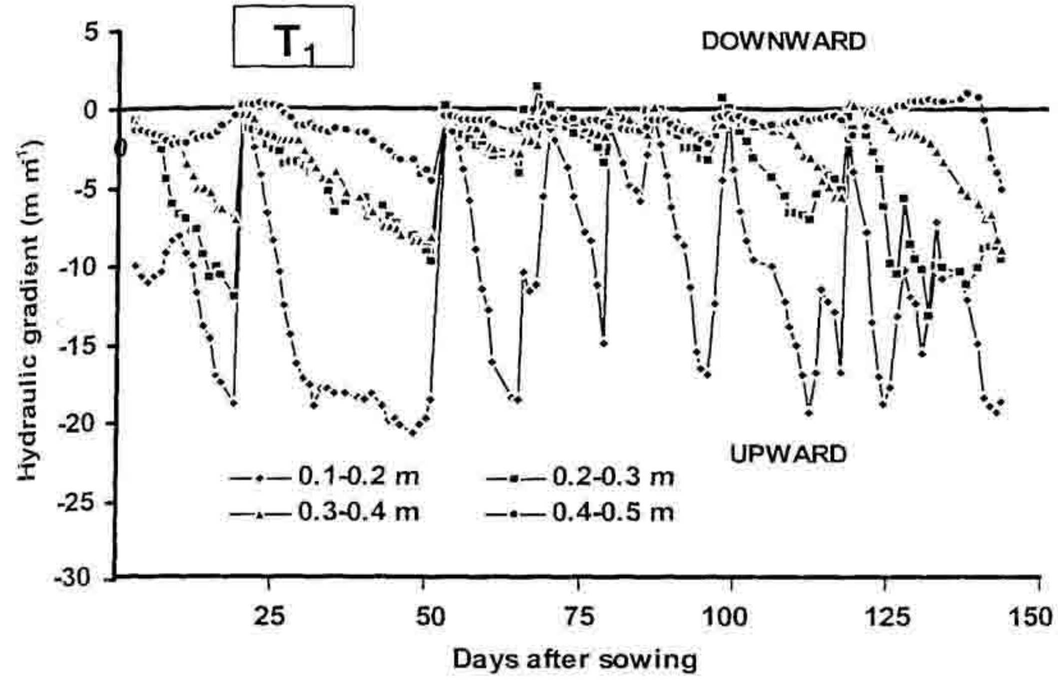


Figure 4.52: Changes in hydraulic gradient with time under tillage treatment T_1 at different depths (m) for the first wheat crop season (2002- 03)

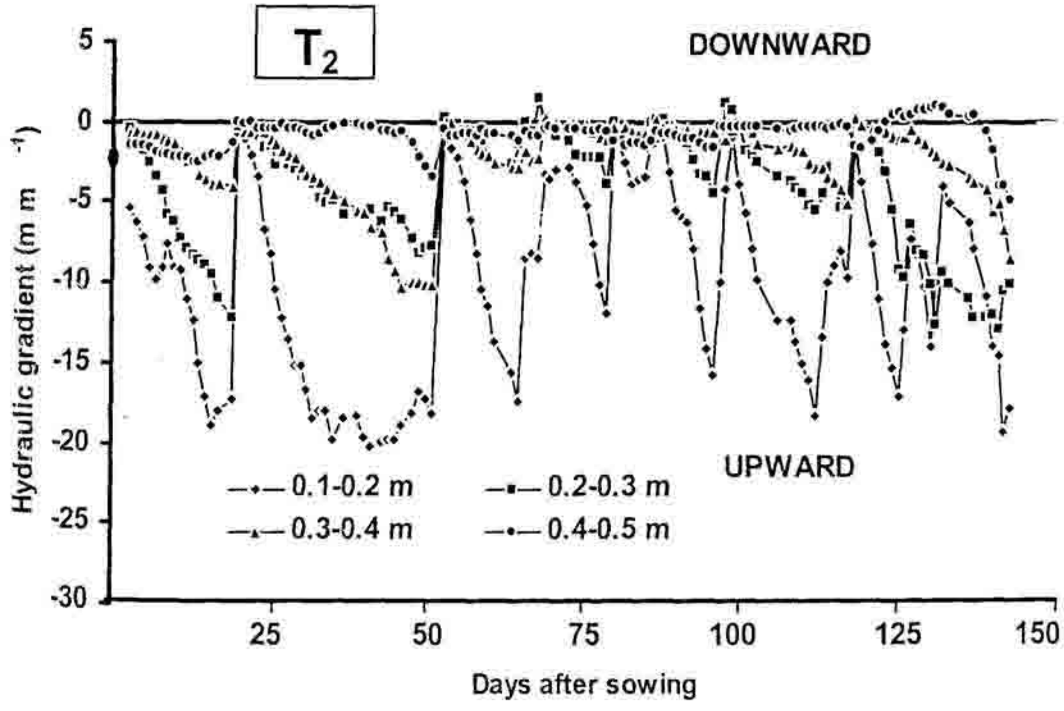


Figure 4.53: Changes in hydraulic gradient with time under tillage treatment T_2 at different depths (m) for the first wheat crop season (2002- 03)

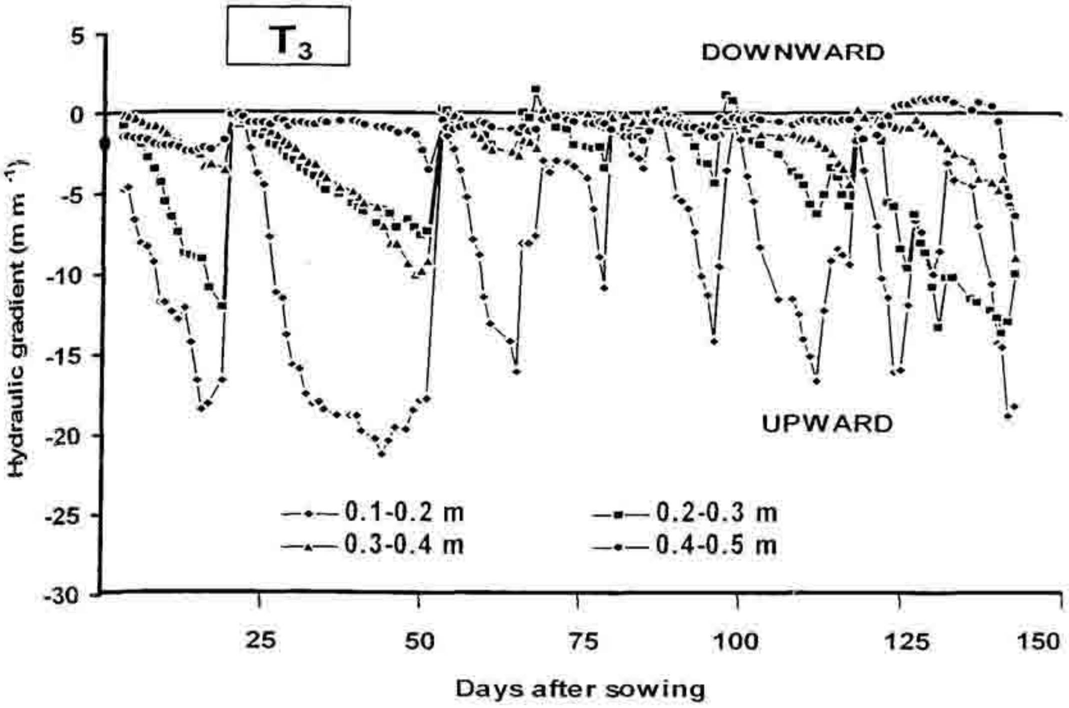


Figure 4.54: Changes in hydraulic gradient with time under tillage treatment T_3 at different depths (m) for the first wheat crop season (2002- 03)

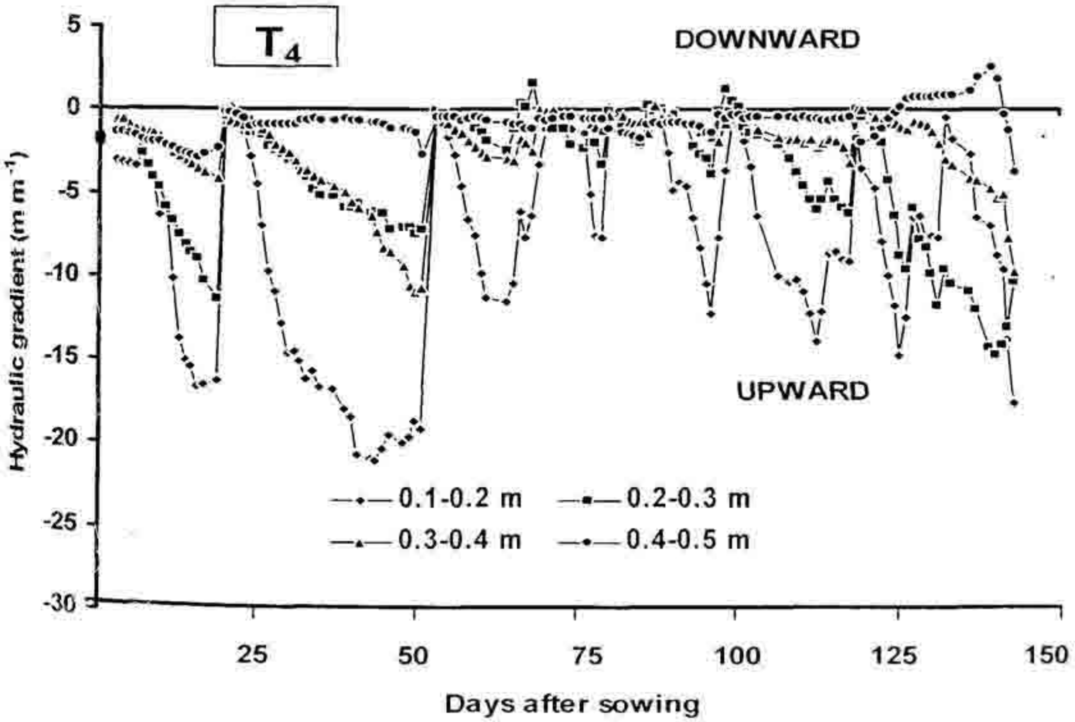


Figure 4.55: Changes in hydraulic gradient with time under tillage treatment T_4 at different depths (m) for the first wheat crop season (2002- 03)

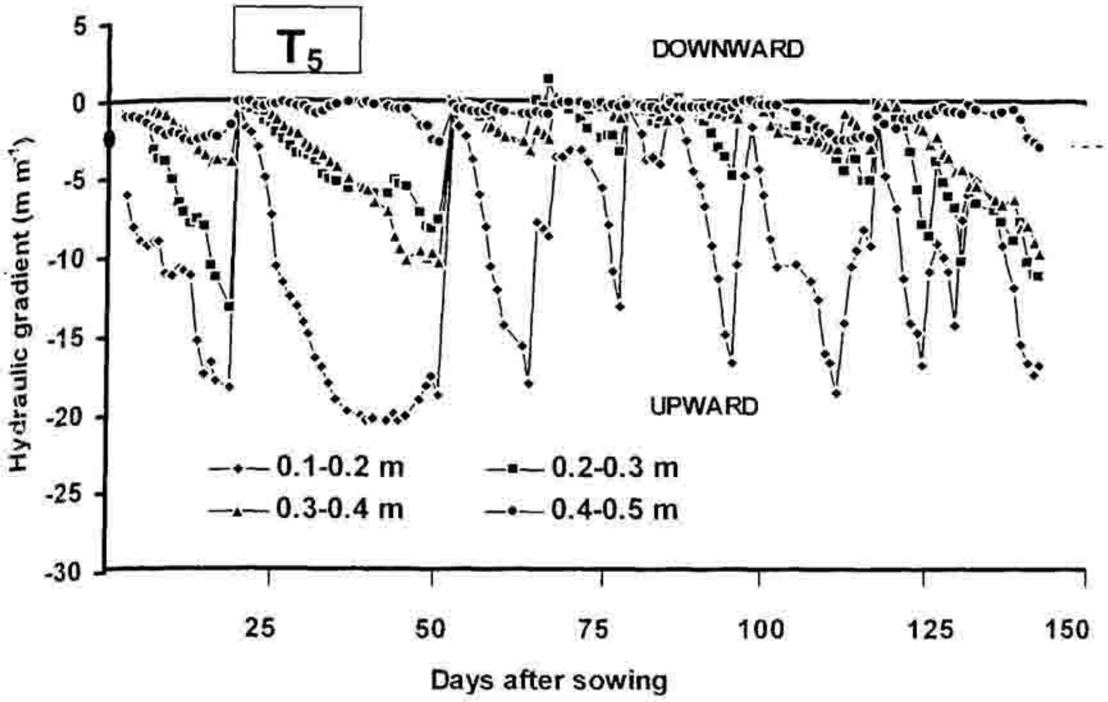


Figure 4.56: Changes in hydraulic gradient with time under tillage treatment T_5 at different depths (m) for the first wheat crop season (2002- 03)

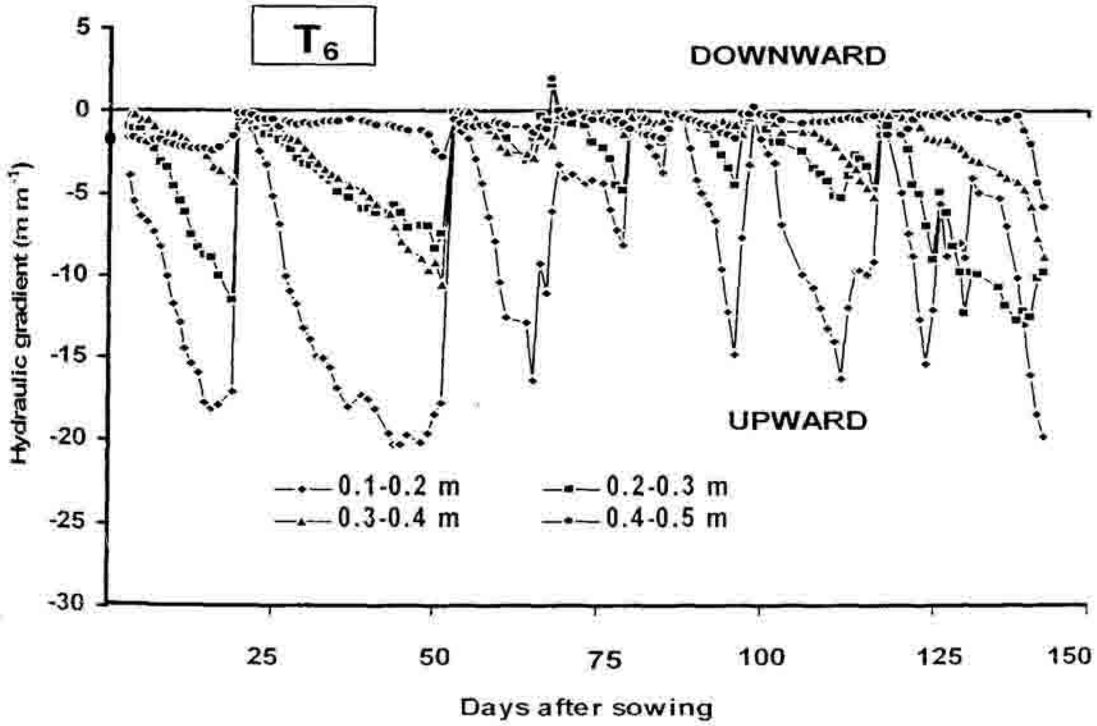


Figure 4.57: Changes in hydraulic gradient with time under tillage treatment T_6 at different depths (m) for the first wheat crop season (2002- 03)

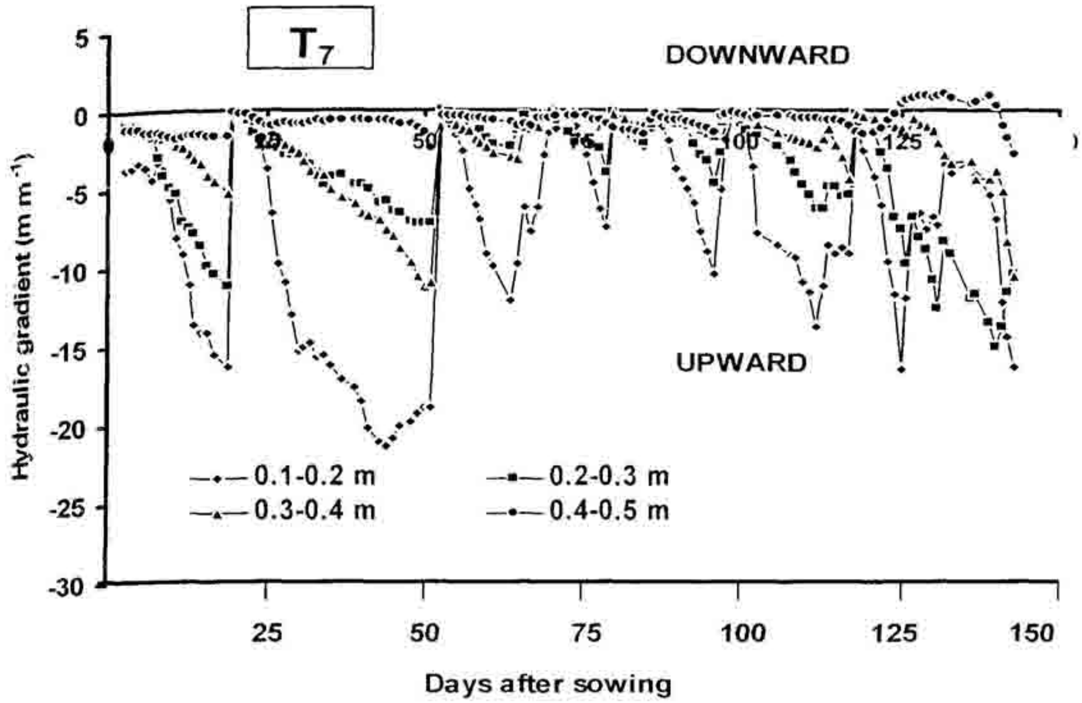


Figure 4.58: Changes in hydraulic gradient with time under tillage treatment T_7 at different depths (m) for the first wheat crop season (2002- 03)

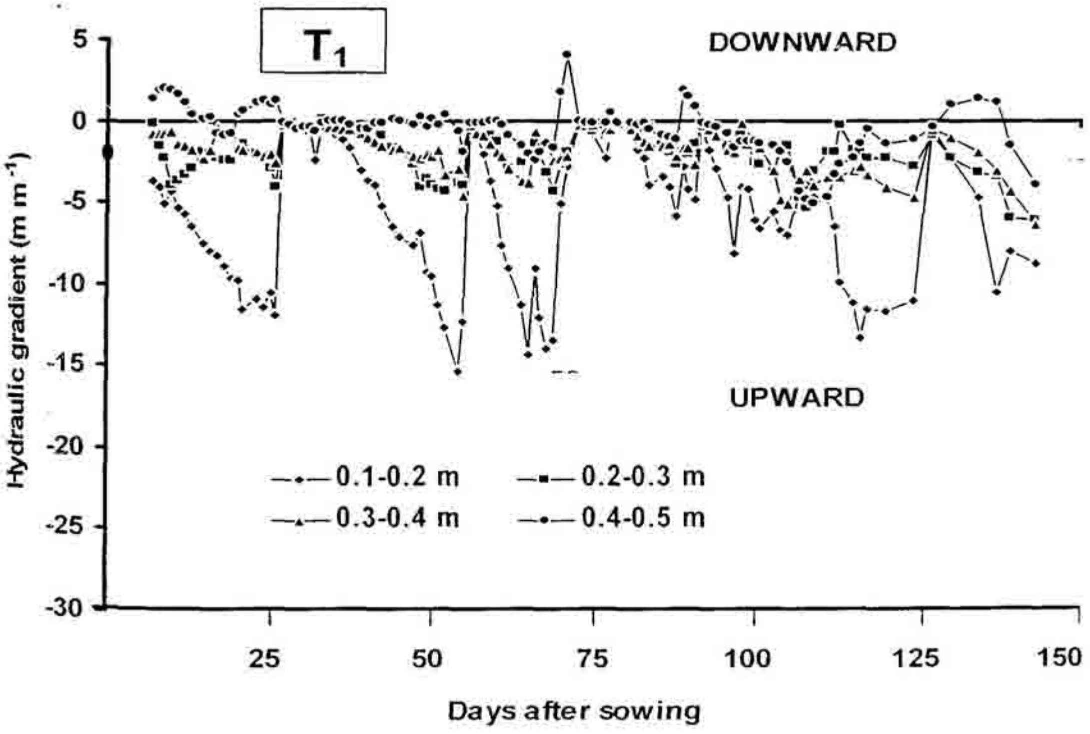


Figure 4.59: Changes in hydraulic gradient with time under tillage treatment T_1 at different depths (m) for the second wheat crop season (2003-04)

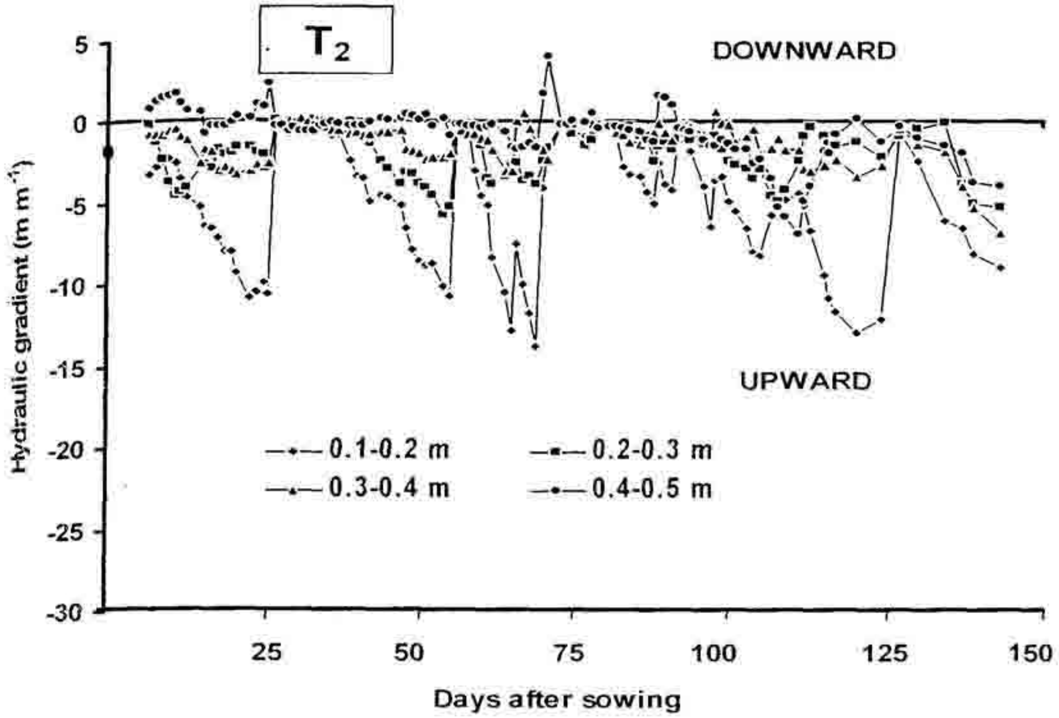


Figure 4.60: Changes in hydraulic gradient with time under tillage treatment T_2 at different depths (m) for the second wheat crop season (2003-04)

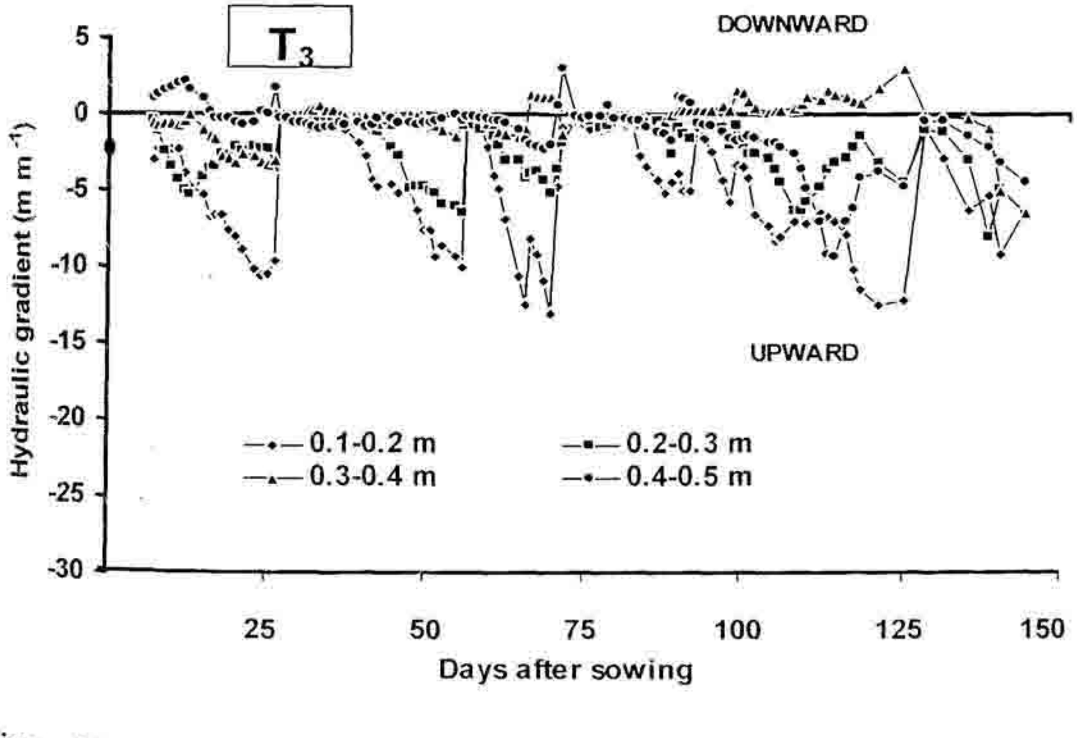


Figure 4.61: Changes in hydraulic gradient with time under tillage treatment T_3 at different depths (m) for the second wheat crop season (2003-04)

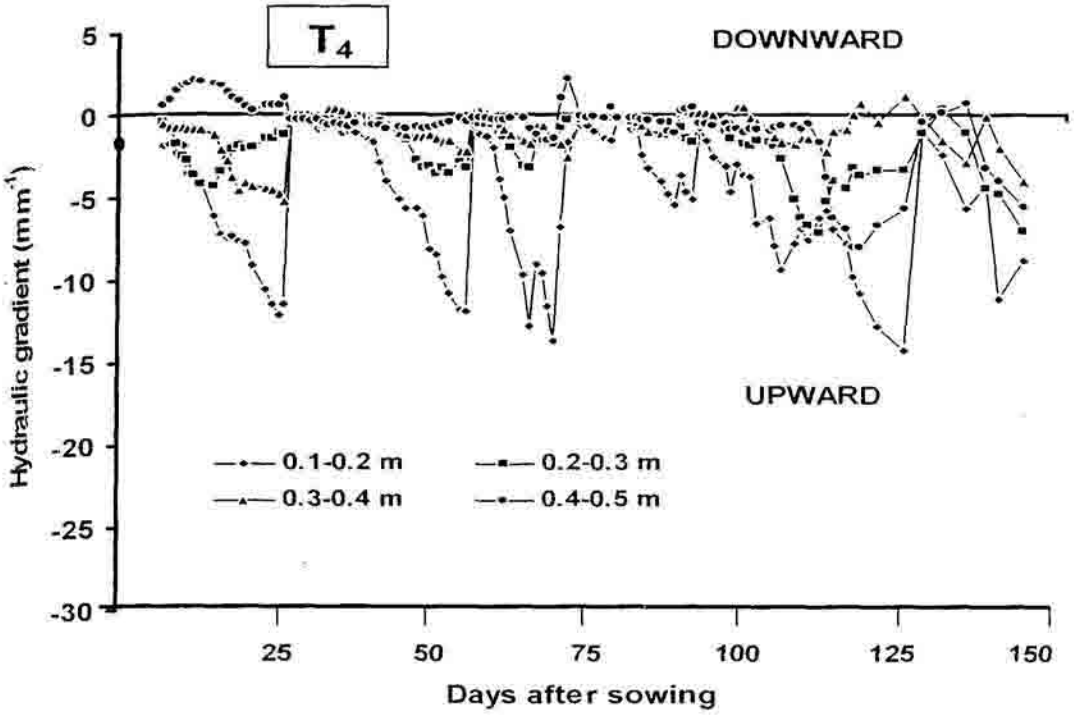


Figure 4.62: Changes in hydraulic gradient with time under tillage treatment T_4 at different depths (m) for the second wheat crop season (2003-04)

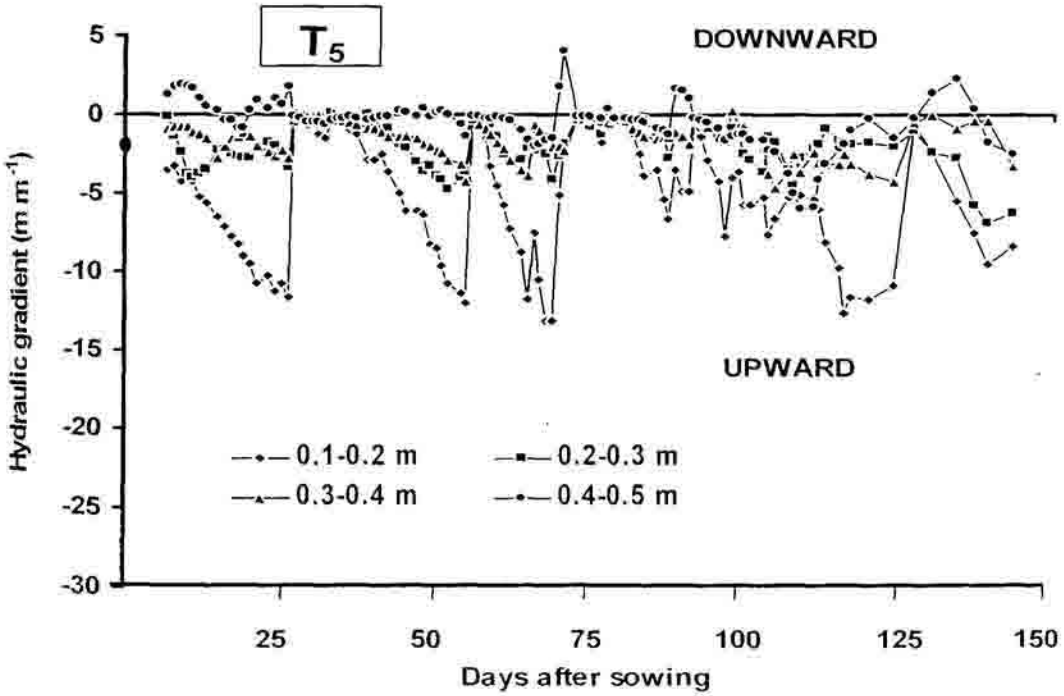


Figure 4.63: Changes in hydraulic gradient with time under tillage treatment T_5 at different depths (m) for the second wheat crop season (2003-04)

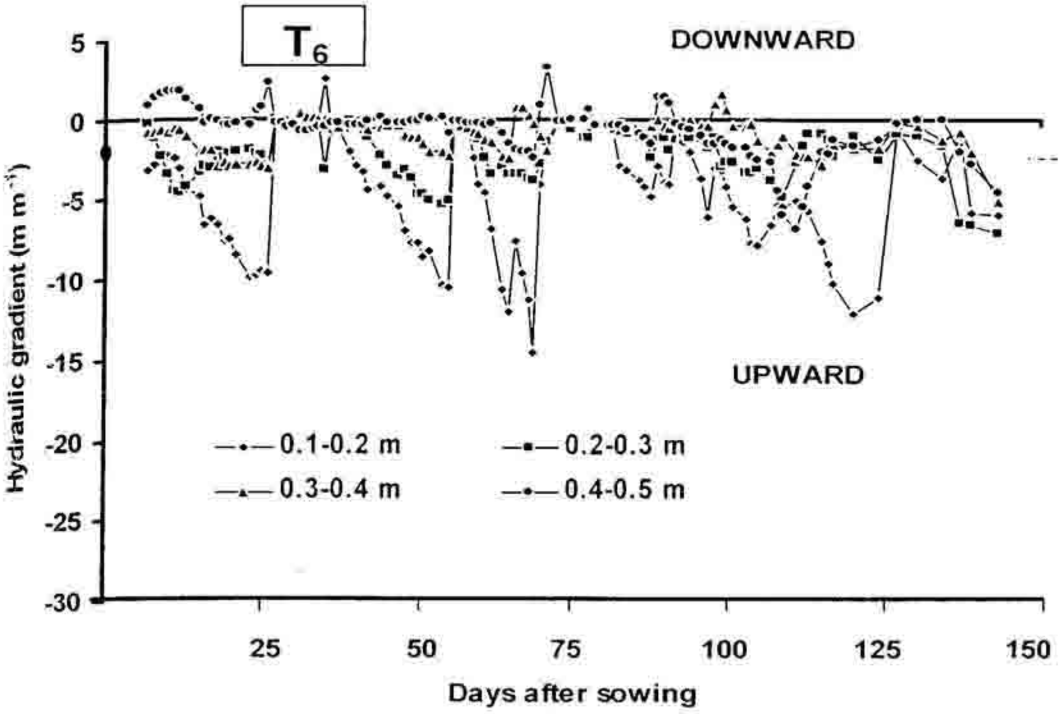


Figure 4.64: Changes in hydraulic gradient with time under tillage treatment T_6 at different depths (m) for the second wheat crop season (2003-04)

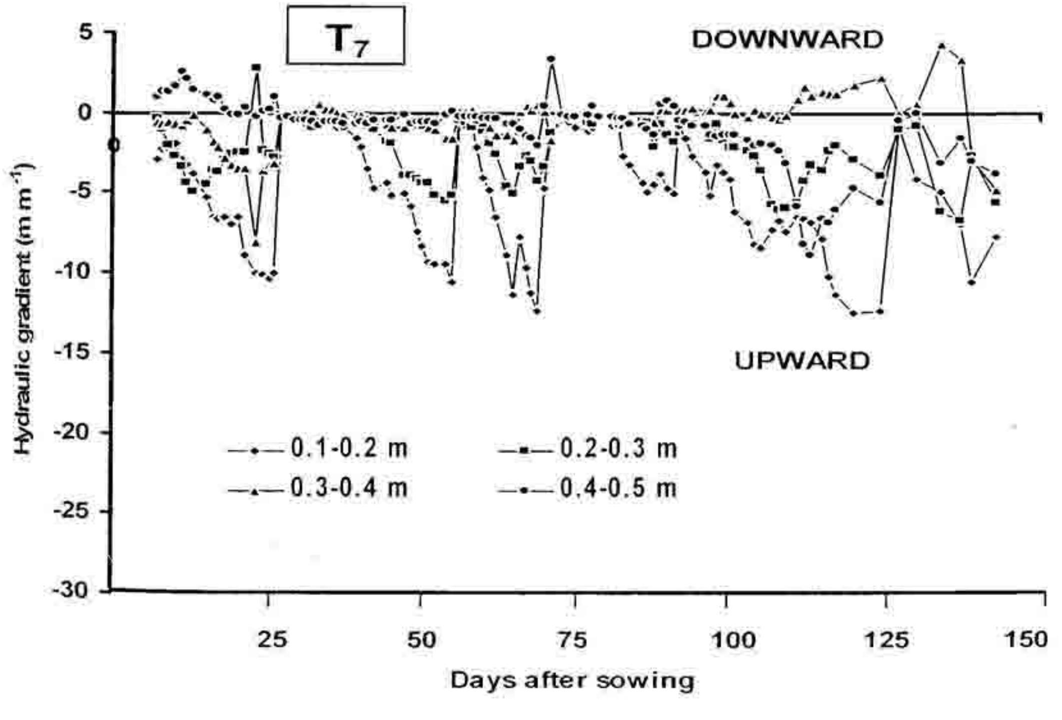


Figure 4.65: Changes in hydraulic gradient with time under tillage treatment T_7 at different depths (m) for the second wheat crop season (2003-04)

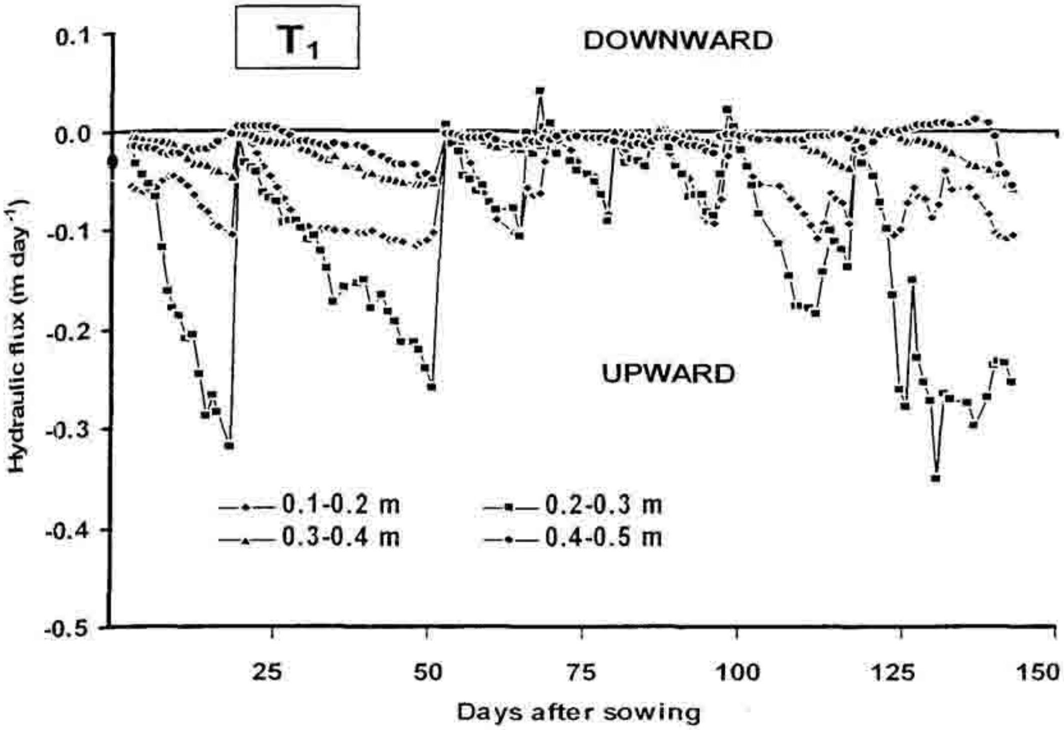


Figure 4.66: Changes in hydraulic flux with time under tillage treatment T_1 at different depths (m) for the first wheat crop season (2002- 03)

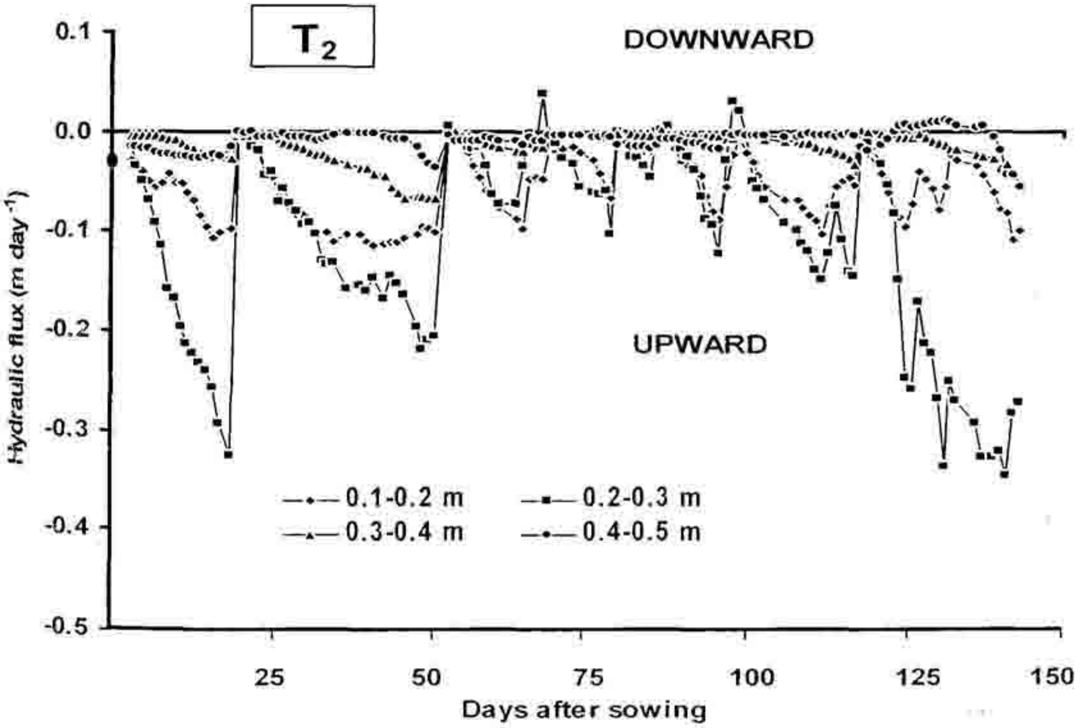


Figure 4.67: Changes in hydraulic flux with time under tillage treatment T_2 at different depths (m) for the first wheat crop season (2002- 03)

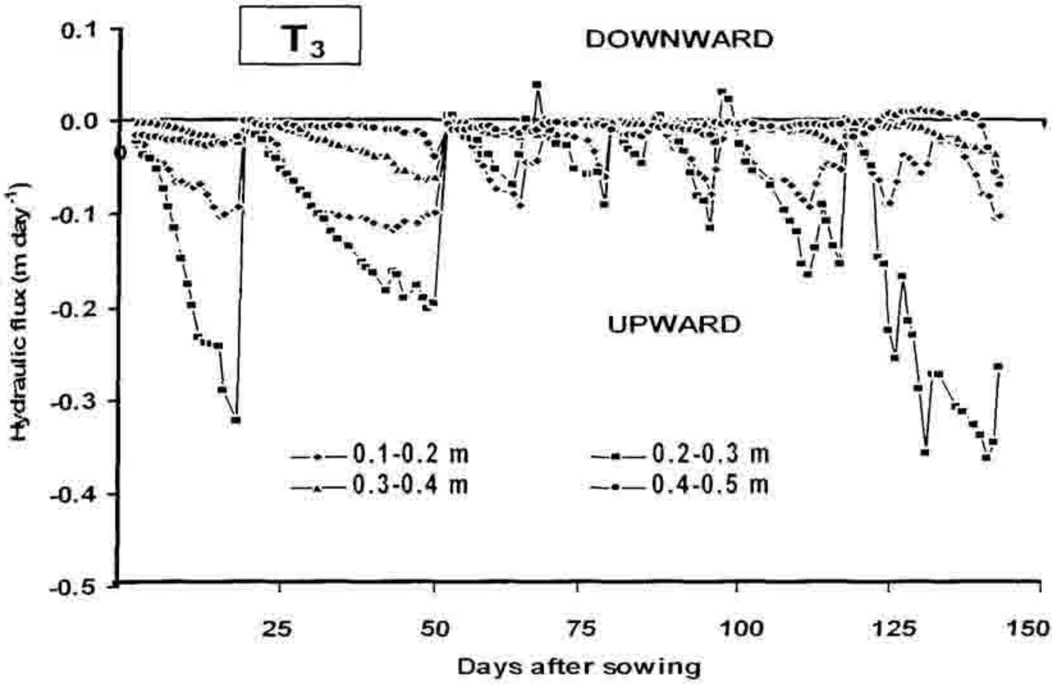


Figure 4.68: Changes in hydraulic flux with time under tillage treatment T_3 at different depths (m) for the first wheat crop season (2002- 03)

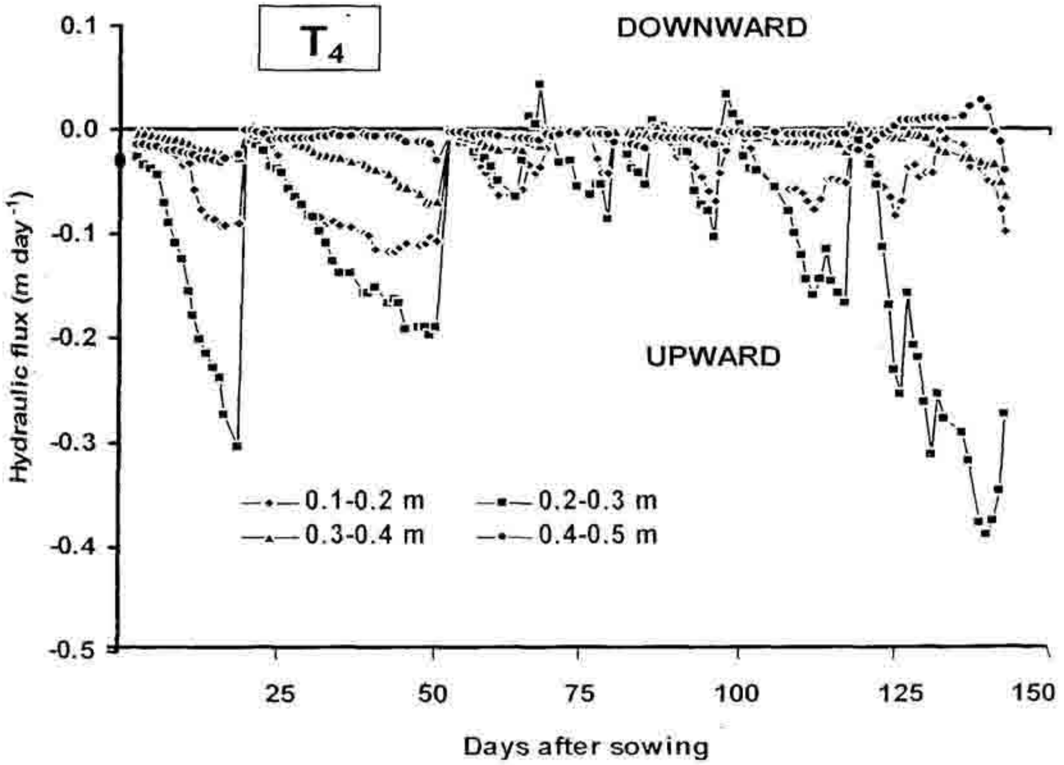


Figure 4.69: Changes in hydraulic flux with time under tillage treatment T_4 at different depths (m) for the first wheat crop season (2002- 03)

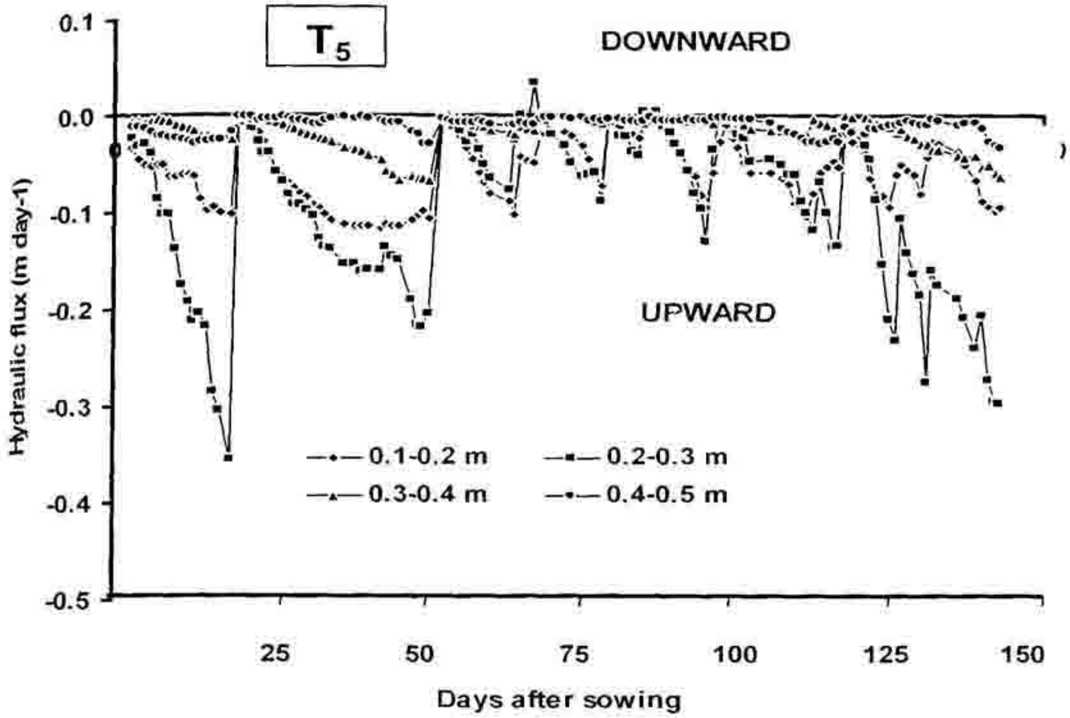


Figure 4.70: Changes in hydraulic flux with time under tillage treatment T_5 at different depths (m) for the first wheat crop season (2002- 03)

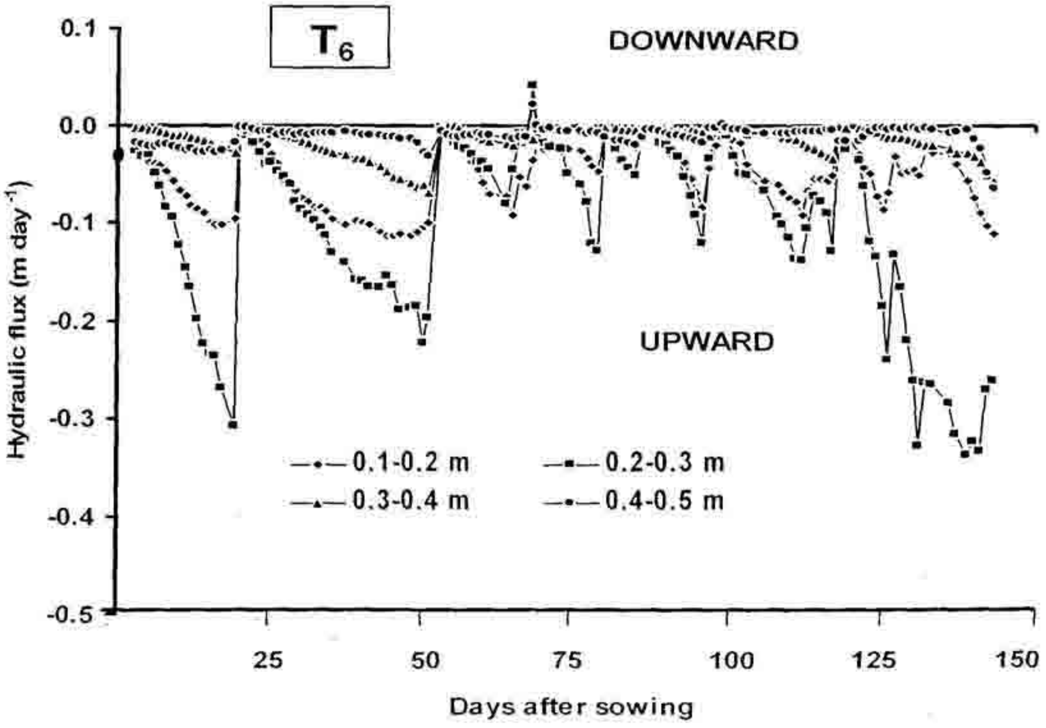


Figure 4.71: Changes in hydraulic flux with time under tillage treatment T_6 at different depths (m) for the first wheat crop season (2002- 03)

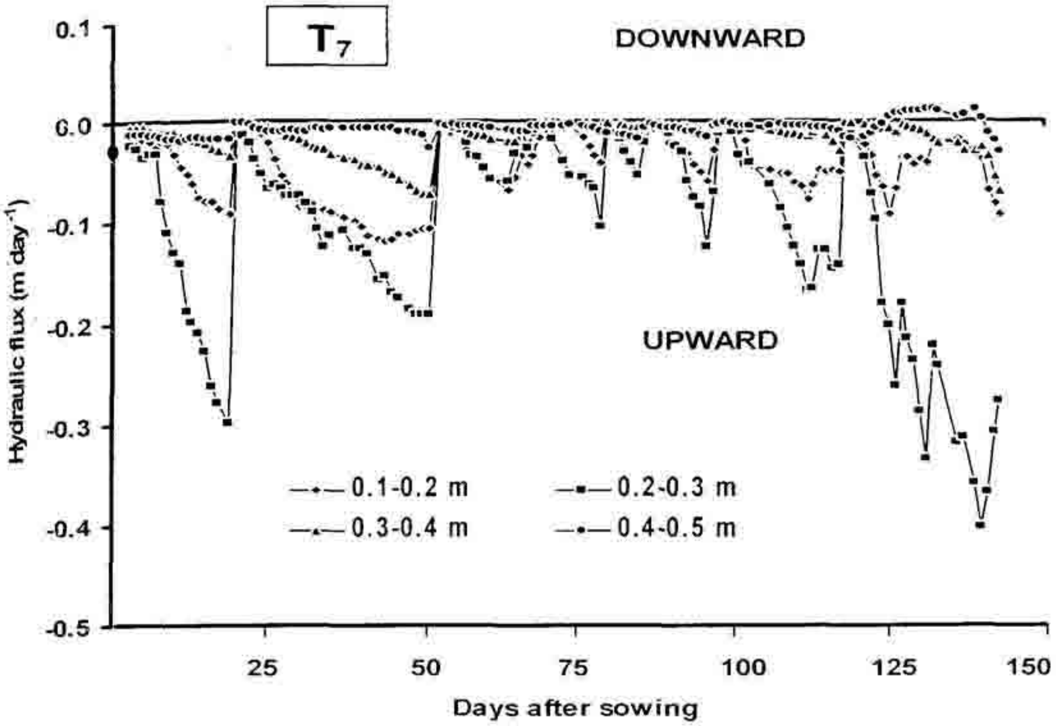


Figure 4.72: Changes in hydraulic flux with time under tillage treatment T_7 at different depths (m) for the first wheat crop season (2002- 03)

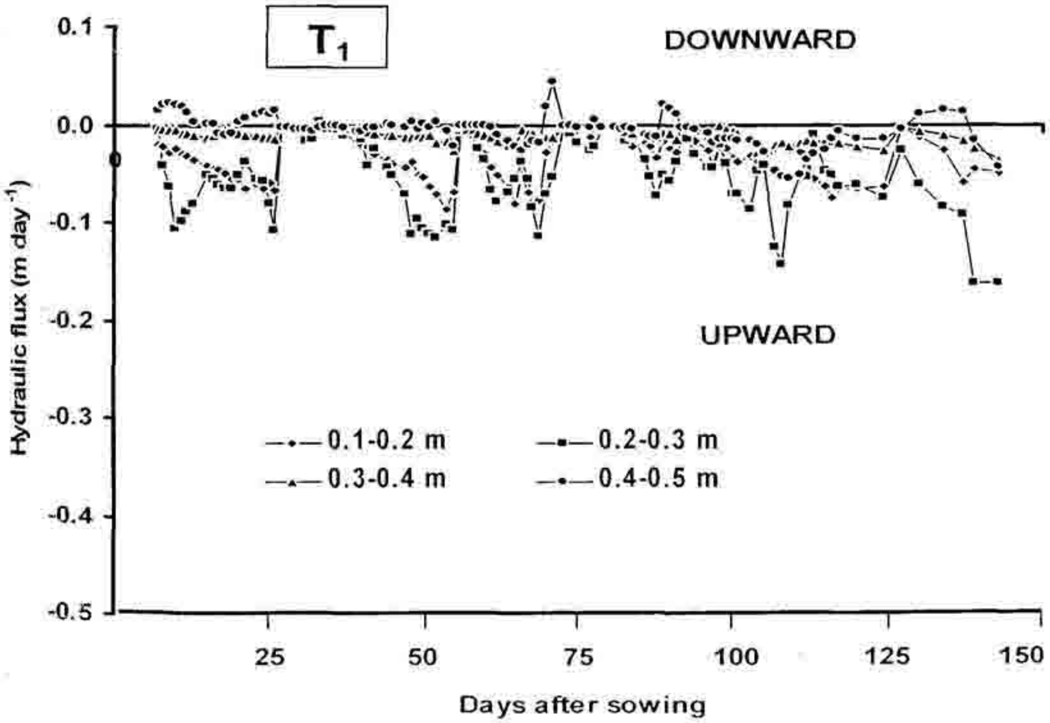


Figure 4.73: Changes in hydraulic flux with time under tillage treatment T_1 at different depths (m) for the second wheat crop season (2003- 04)

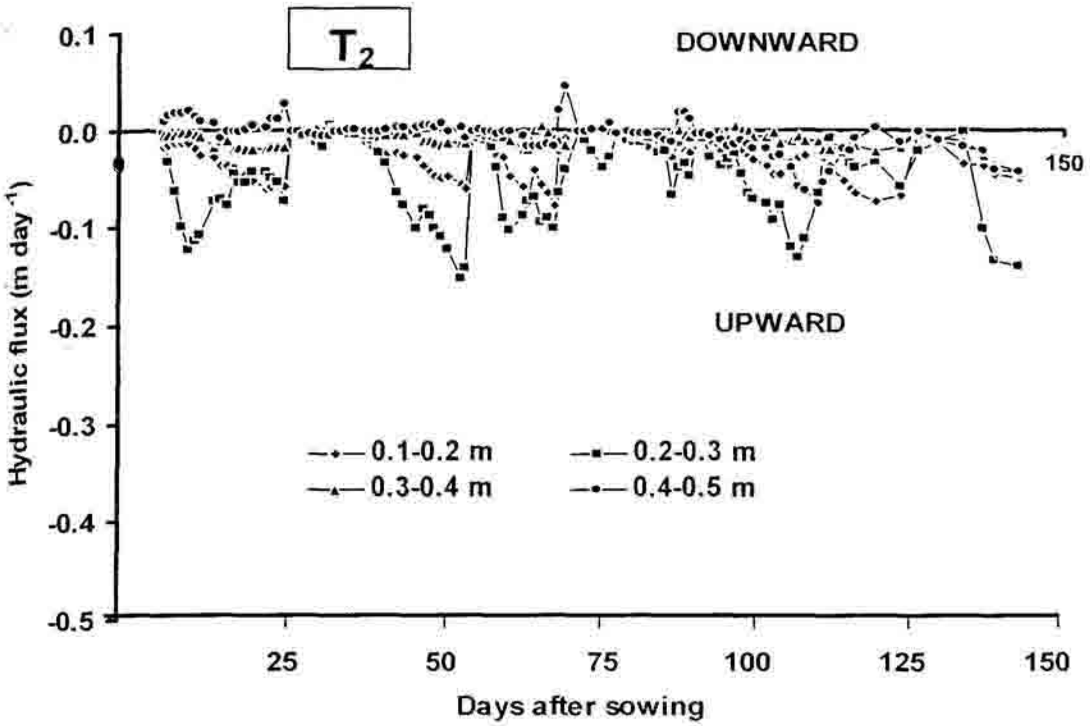


Figure 4.74: Changes in hydraulic flux with time under tillage treatment T_2 at different depths (m) for the second wheat crop season (2003- 04)

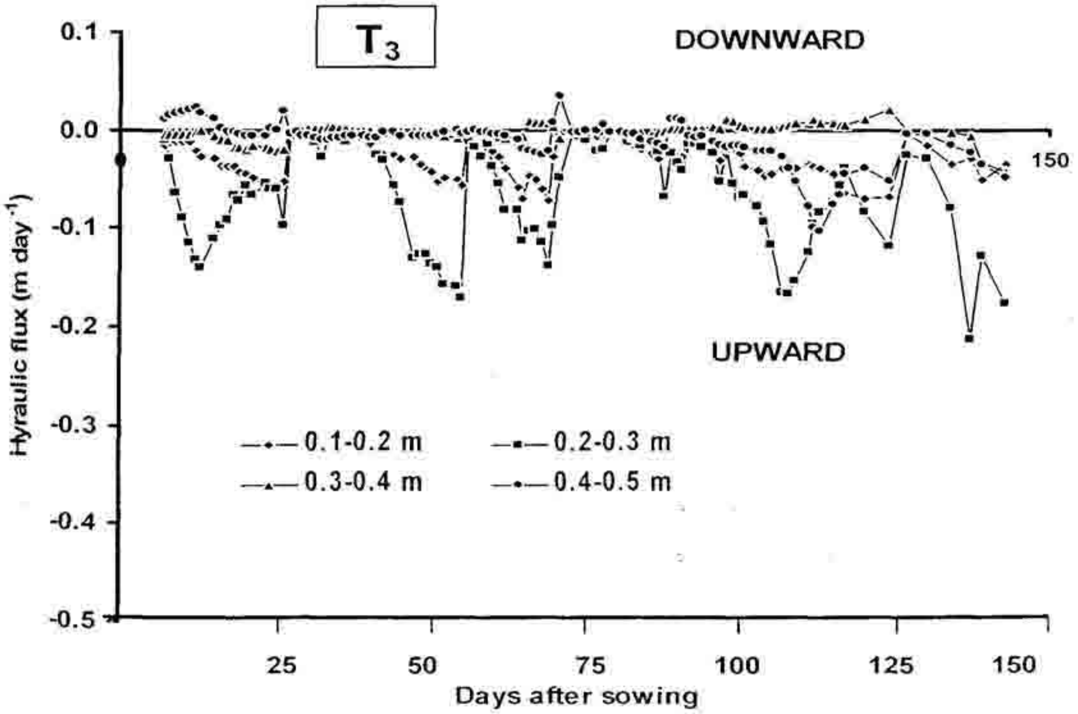


Figure 4.75: Changes in hydraulic flux with time under tillage treatment T_3 at different depths (m) for the second wheat crop season (2003- 04)

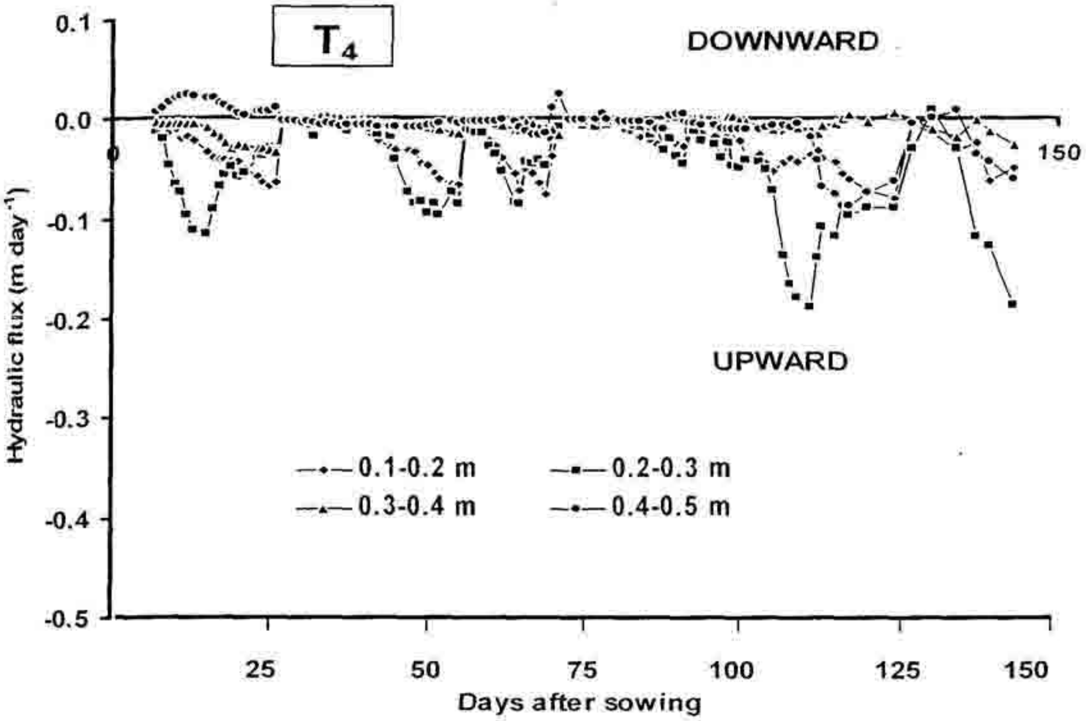


Figure 4.76: Changes in hydraulic flux with time under tillage treatment T_4 at different depths (m) for the second wheat crop season (2003- 04)

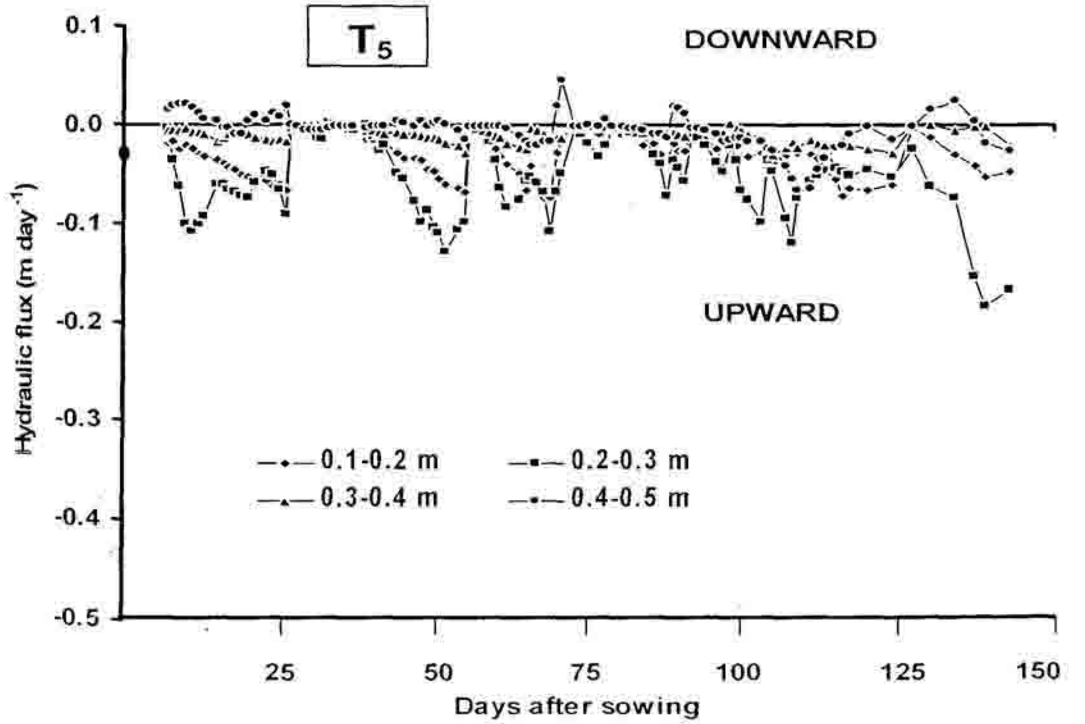


Figure 4.77: Changes in hydraulic flux with time under tillage treatment T_5 at different depths (m) for the second wheat crop season (2003- 04)

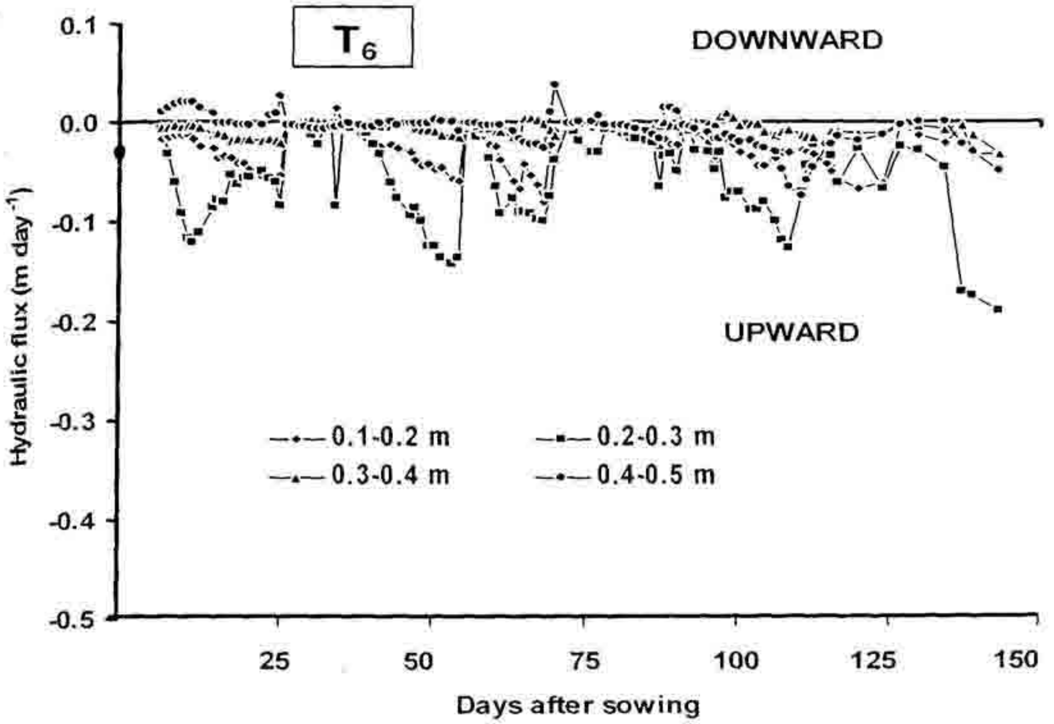


Figure 4.78: Changes in hydraulic flux with time under tillage treatment T_6 at different depths (m) for the second wheat crop season (2003- 04)

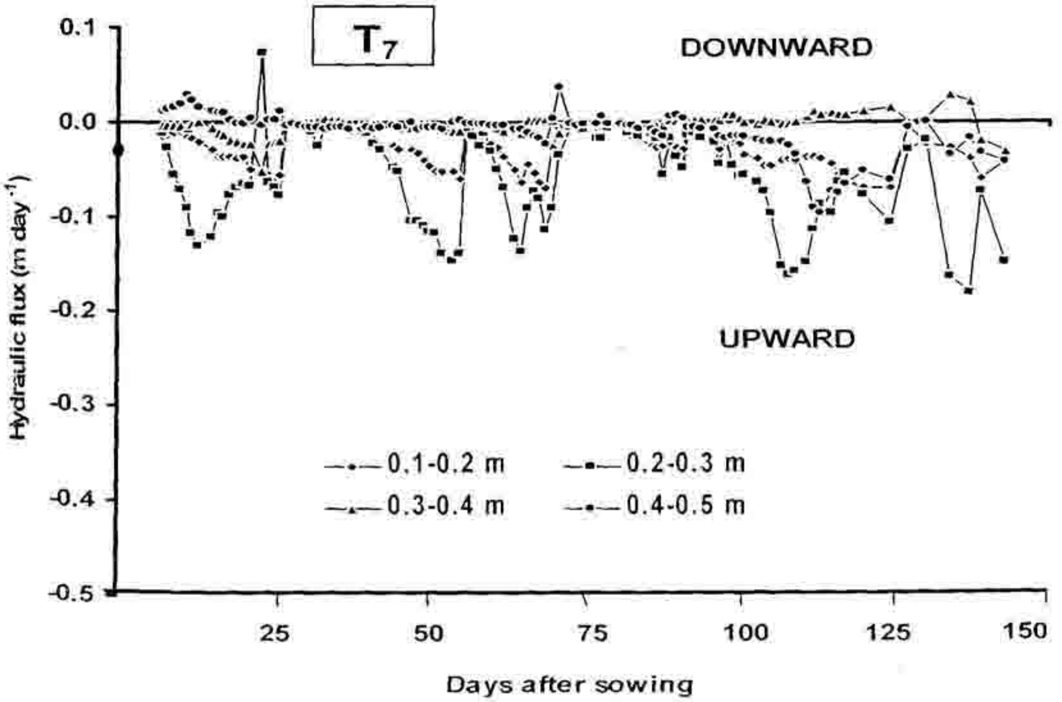


Figure 4.79: Changes in hydraulic flux with time under tillage treatment T_7 at different depths (m) for the second wheat crop season (2003- 04)

sowing during first year. However, during the second year, a discernable downward flux was observed for 0.4-0.5 m soil depth of during initial 7 to 23 days after sowing.

4.3.2.6 Infiltration rate

The effect of different tillage treatments on infiltration rate (i) and accumulative intake (I) after harvest of first and second wheat crop are depicted in Figure 4.80, 4.81, 4.82, 4.83, 4.84, 4.85 and 4.86 (2002-03) and Figure 4.87, 4.88, 4.89, 4.90, 4.91, 4.92 and 4.93 (2003-04), respectively. These figures present typical infiltration-time curves of the study area. The final infiltration rate and accumulated intake during both years of wheat study were lower under T_1 as compared to all of the other treatments.

During first wheat crop season, the steady-state infiltration rate (cm hr^{-1}) at harvest was higher in T_7 (4.95) as compared with T_1 (0.85), T_2 (1.71), T_3 (3.67), T_4 (4.81), T_5 (1.47) and T_6 (3.77) (Figure 4.52, 4.53, 4.54, 4.55, 4.56, 4.57 and 4.58) and in second year, it was higher under T_4 (4.91) as compared with T_1 (0.72), T_2 (1.68), T_3 (3.34), T_5 (1.10), T_6 (2.35) and T_7 (3.32) (Figure 4.59, 4.60, 4.61, 4.62, 4.63, 4.64 and 4.65). The accumulated intake (cm) during first wheat crop season at harvest was higher in T_7 (64.78) as compared with T_1 (17.64), T_2 (28.21), T_3 (51.32), T_4 (62.86), T_5 (25.21) and T_6 (49.01) (Figure 4.52, 4.53, 4.54, 4.55, 4.56, 4.57 and 4.58) and in second year, it was higher under T_4 (64.46) as compared with T_1 (19.76), T_2 (29.53), T_3 (50.08), T_5 (23.78), T_6 (32.37) and T_7 (48.73) (Figure 4.59, 4.60, 4.61, 4.62, 4.63, 4.64 and 4.65). The steady-state infiltration was achieved in both cases in about 8 to 10

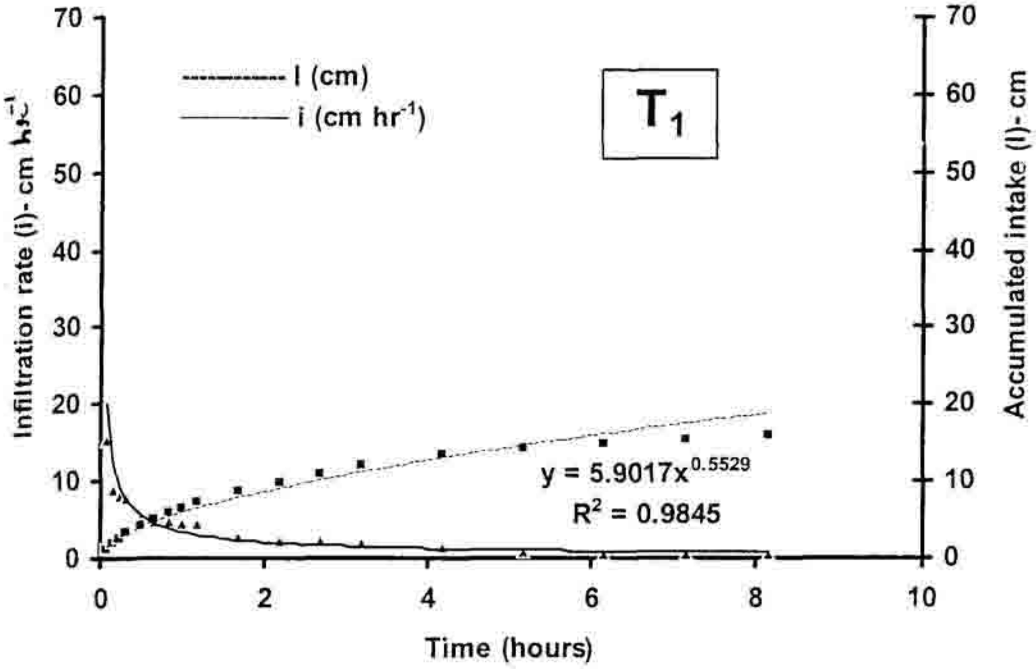


Figure 4.80: Infiltration-time curve under tillage treatment T_1 at post harvest of first wheat crop season (2002- 03)

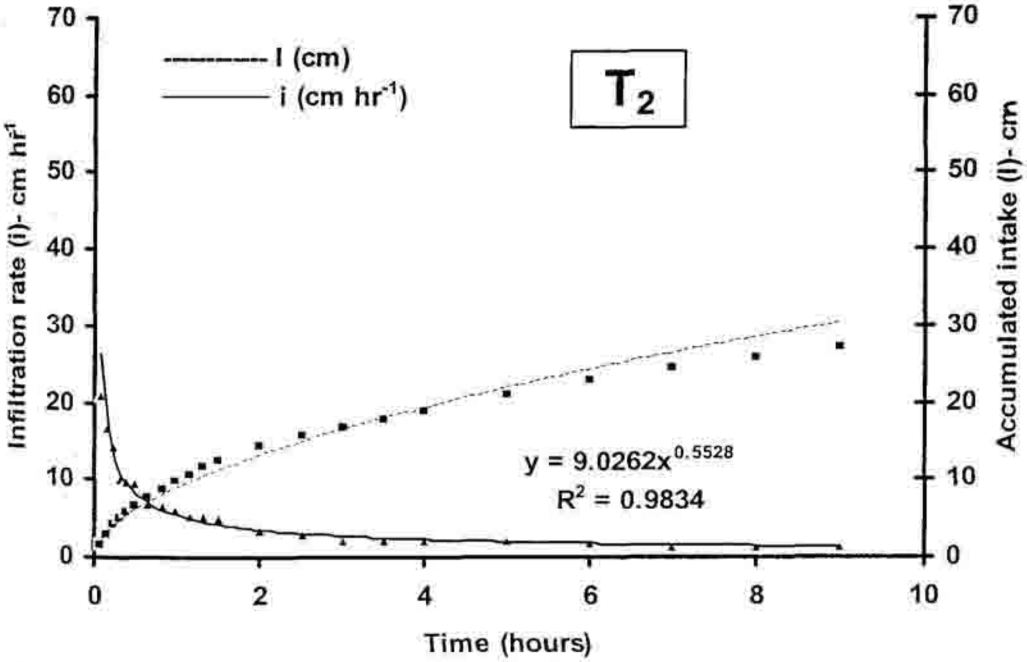


Figure 4.81: Infiltration-time curve under tillage treatment T_2 at post harvest of first wheat crop season (2002- 03)

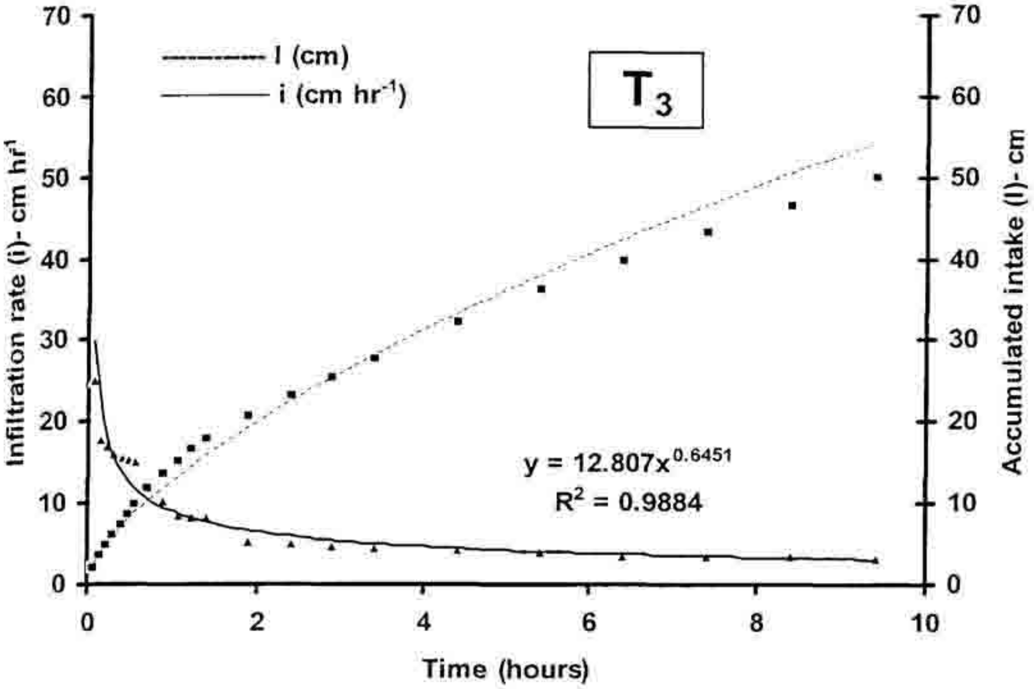


Figure 4.82: Infiltration-time curve under tillage treatment T_3 at post harvest of first wheat crop season (2002- 03)

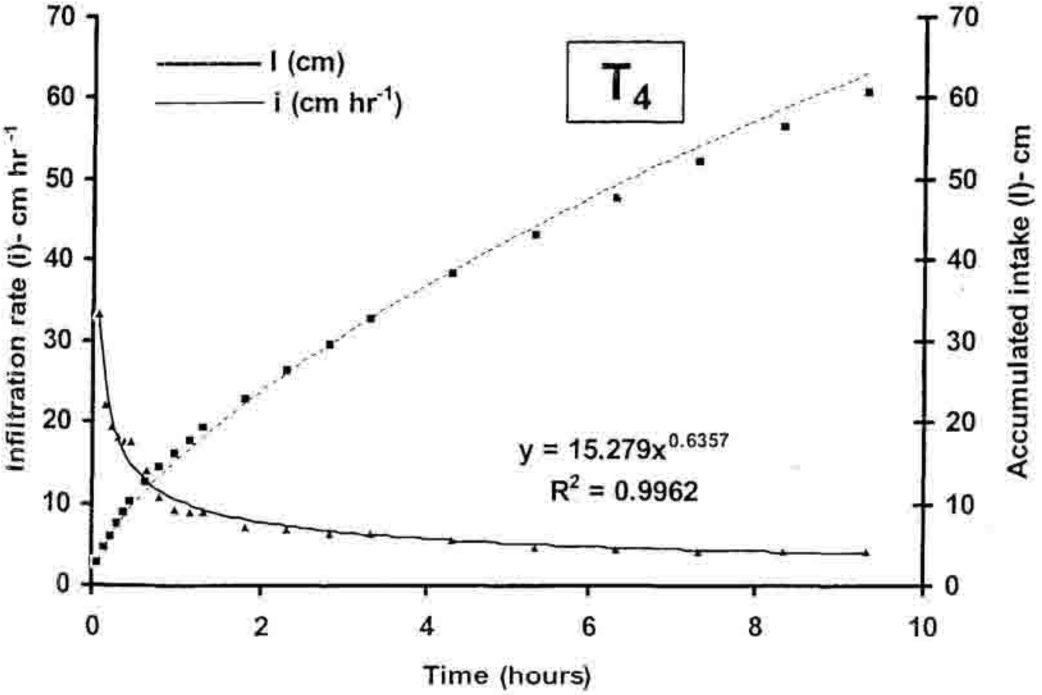


Figure 4.83: Infiltration-time curve under tillage treatment T_4 at post harvest of first wheat crop season (2002- 03)

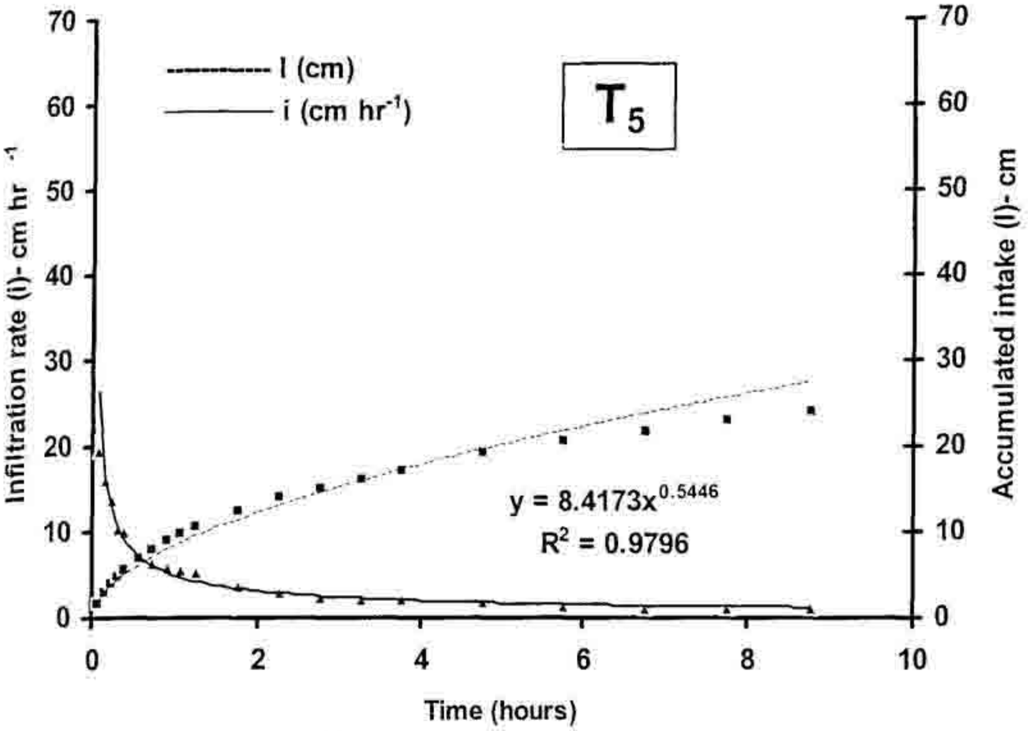


Figure 4.84: Infiltration-time curve under tillage treatment T_5 at post harvest of first wheat crop season (2002- 03)

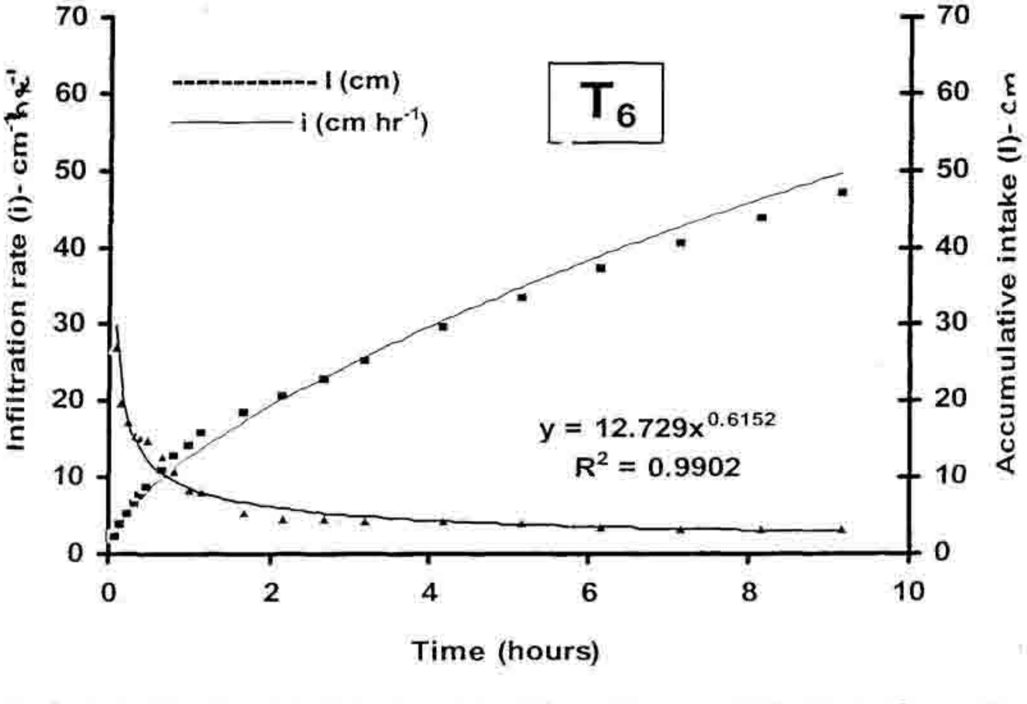


Figure 4.85: Infiltration-time curve under tillage treatment T_6 at post harvest of first wheat crop season (2002- 03)

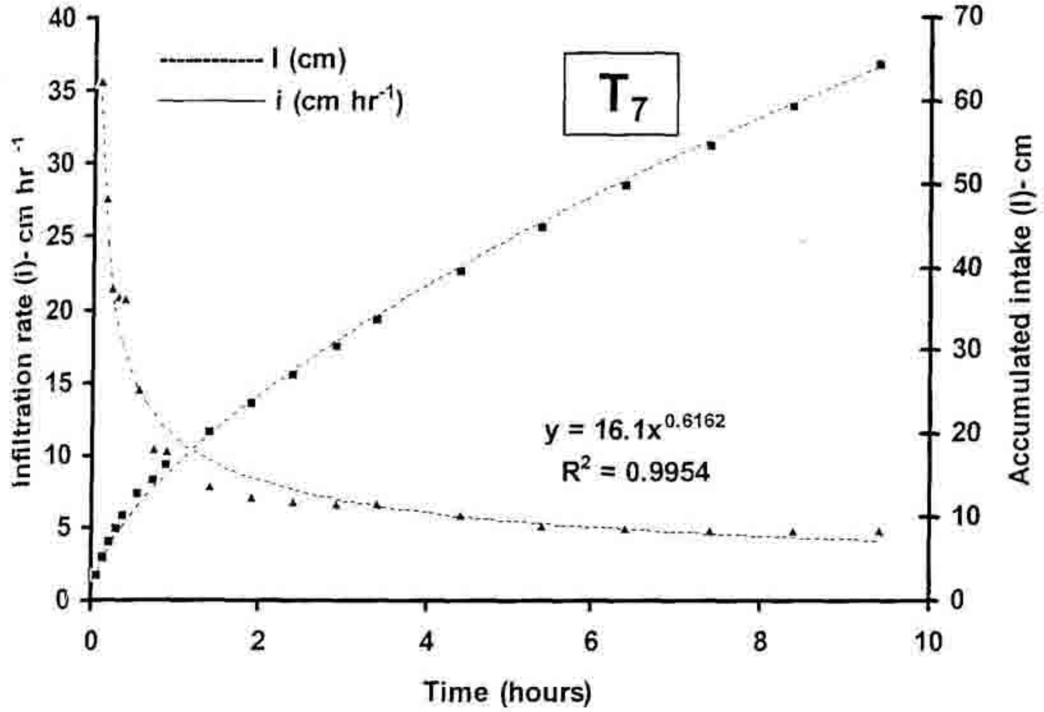


Figure 4.86: Infiltration- time curve under tillage treatment T_7 at post harvest of first wheat crop season (2002- 03)

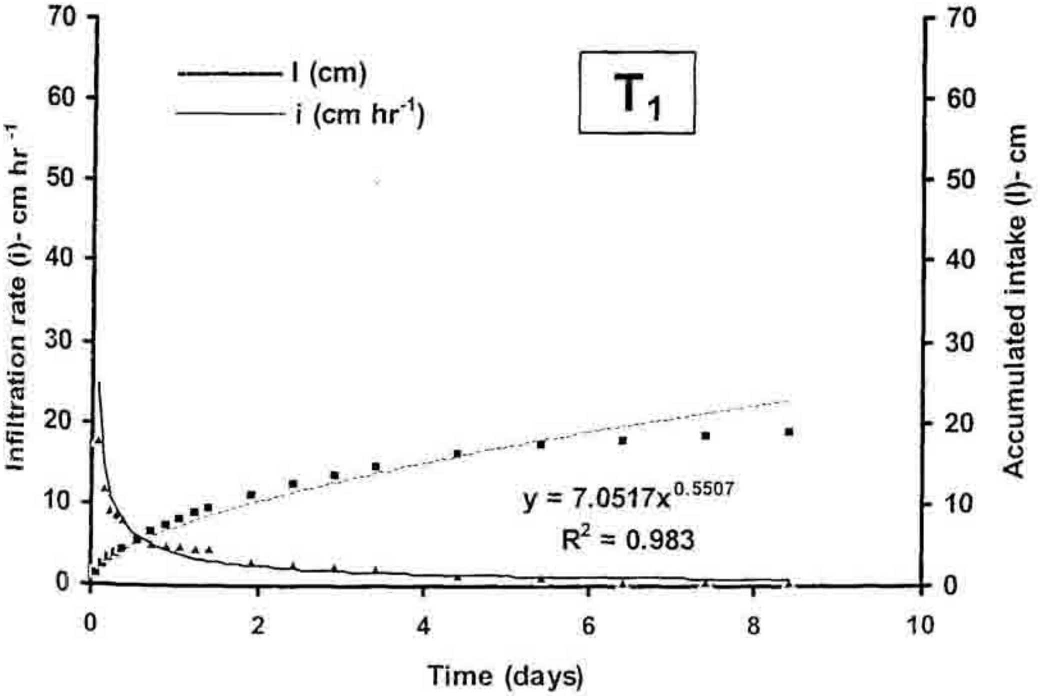


Figure 4.87: Infiltration-time curve under tillage treatment T_1 at post harvest of second wheat crop season (2003- 04)

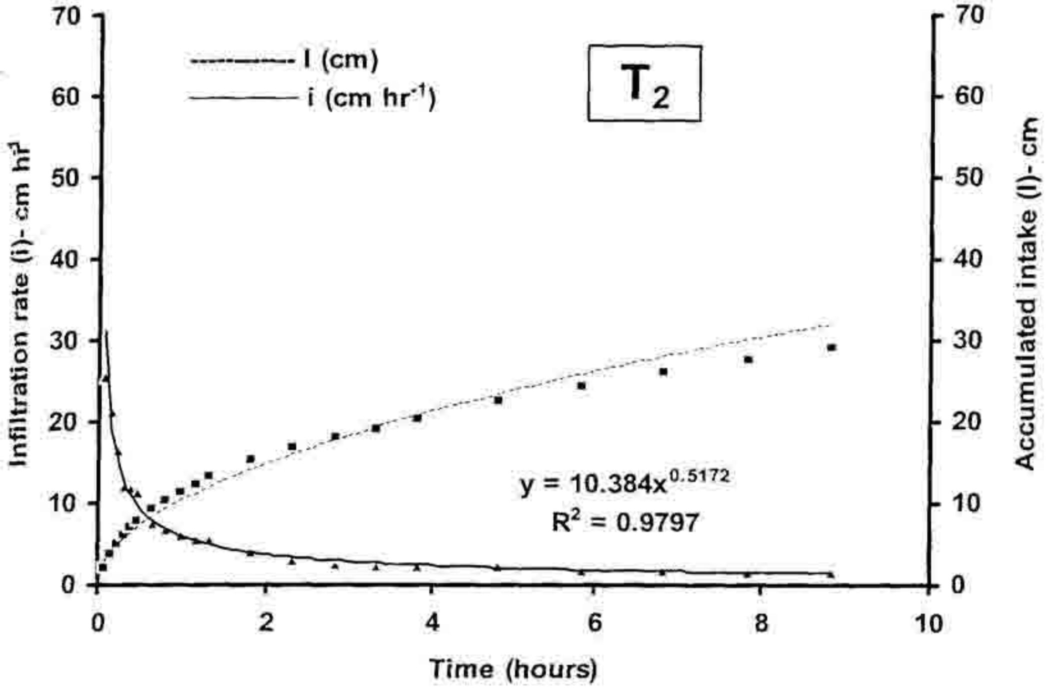


Figure 4.88: Infiltration-time curve under tillage treatment T_2 at post harvest of second wheat crop season (2003- 04)

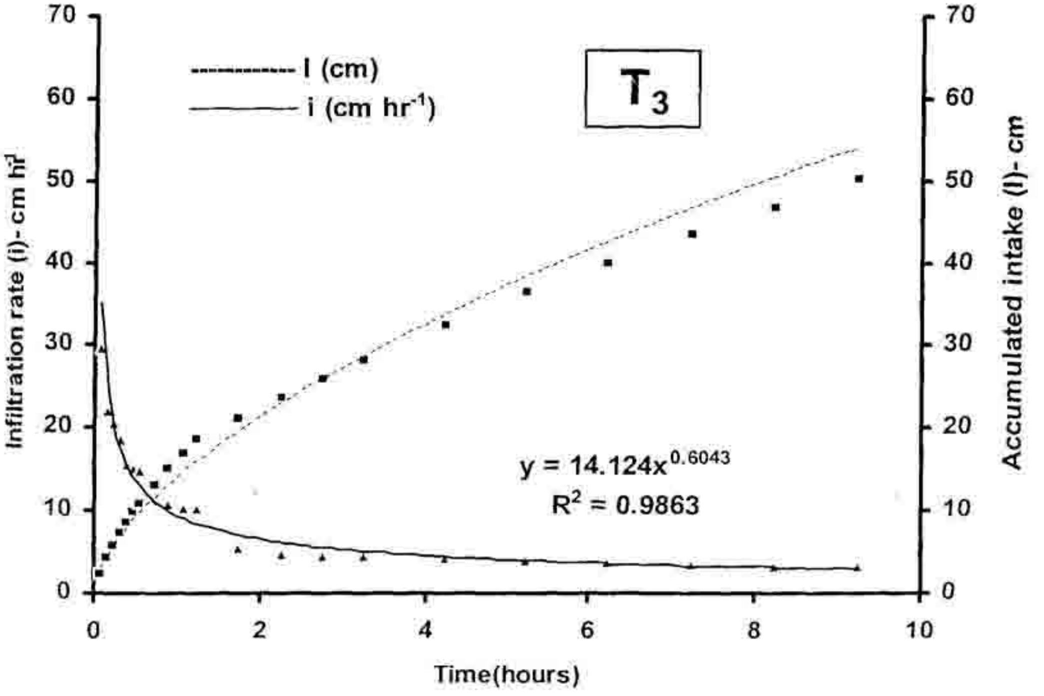


Figure 4.89: Infiltration-time curve under tillage treatment T_3 at post harvest of second wheat crop season (2003- 04)

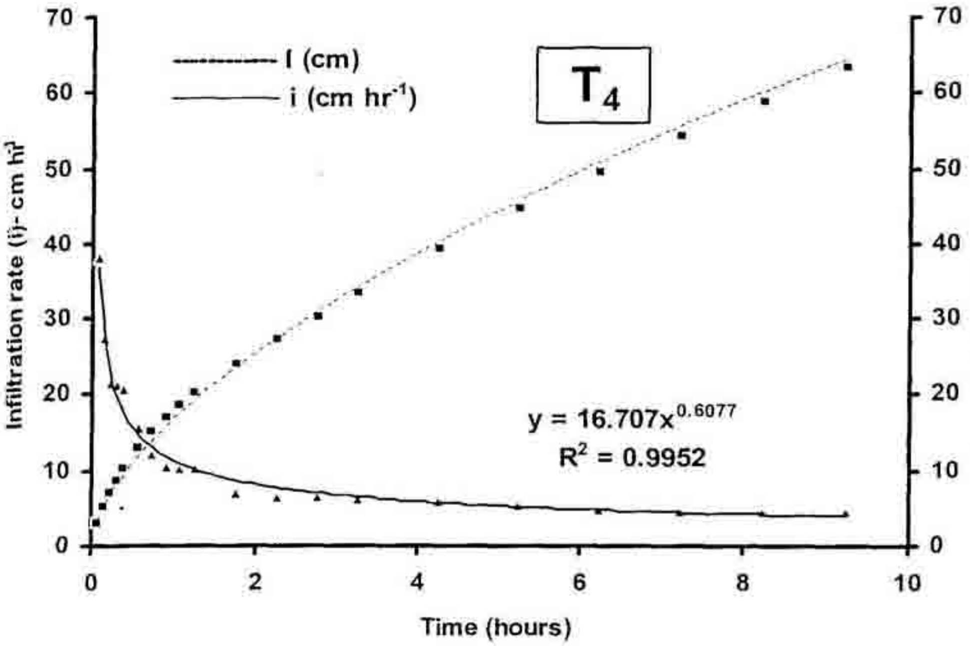


Figure 4.90: Infiltration-time curve under tillage treatment T_4 at post harvest of second wheat crop season (2003- 04)

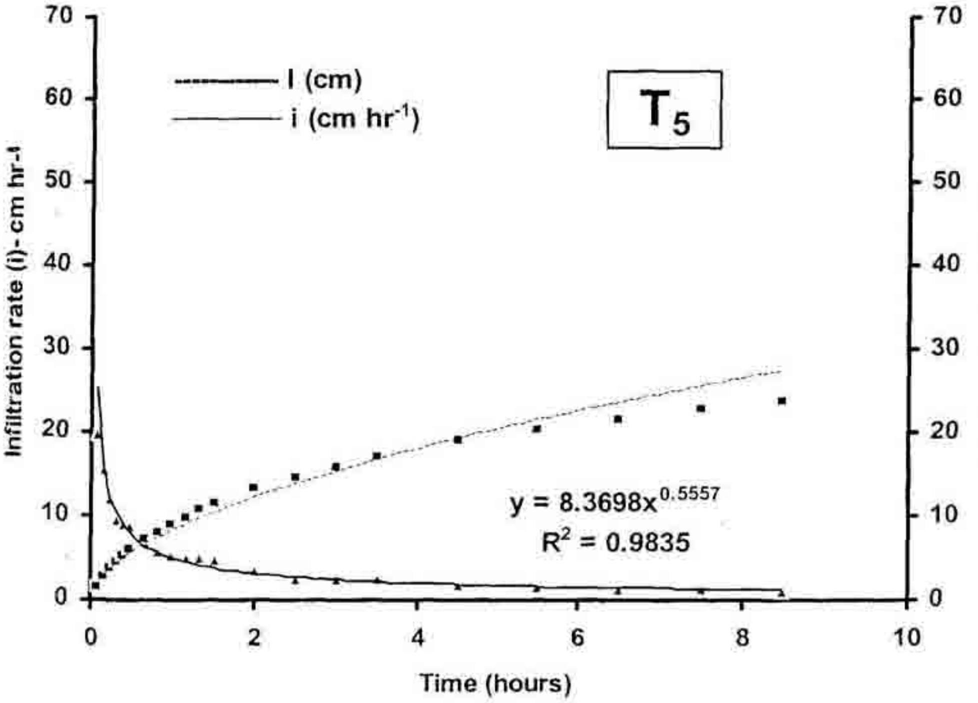


Figure 4.91: Infiltration-time curve under tillage treatment T_5 at post harvest of second wheat crop season (2003- 04)

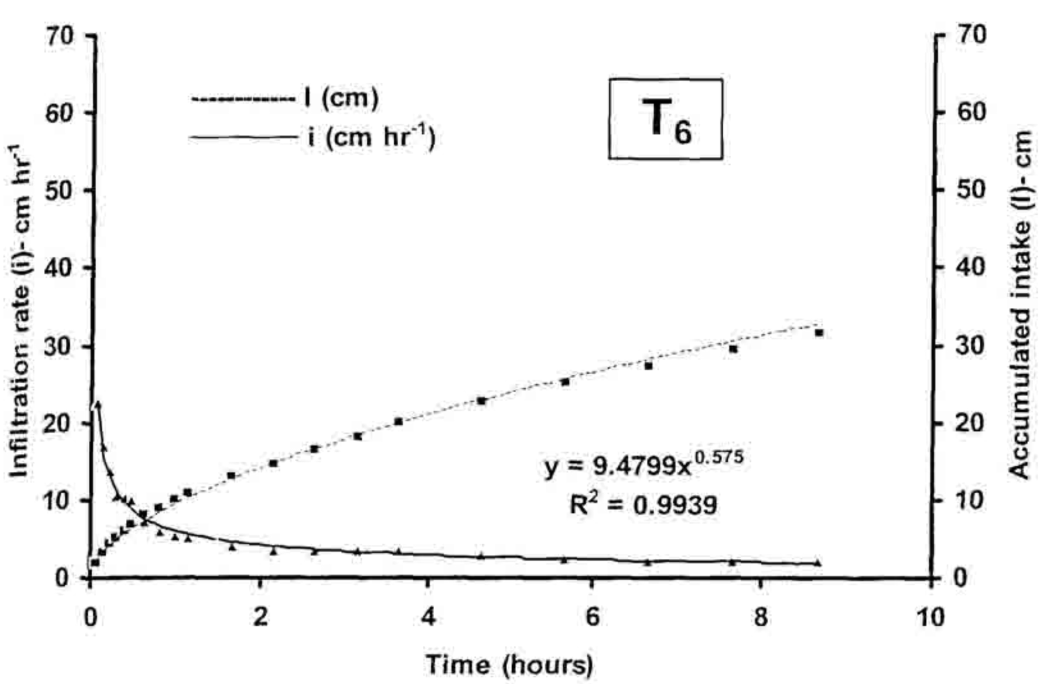


Figure 4.92: Infiltration-time curve under tillage treatment T_6 at post harvest of second wheat crop season (2003- 04)

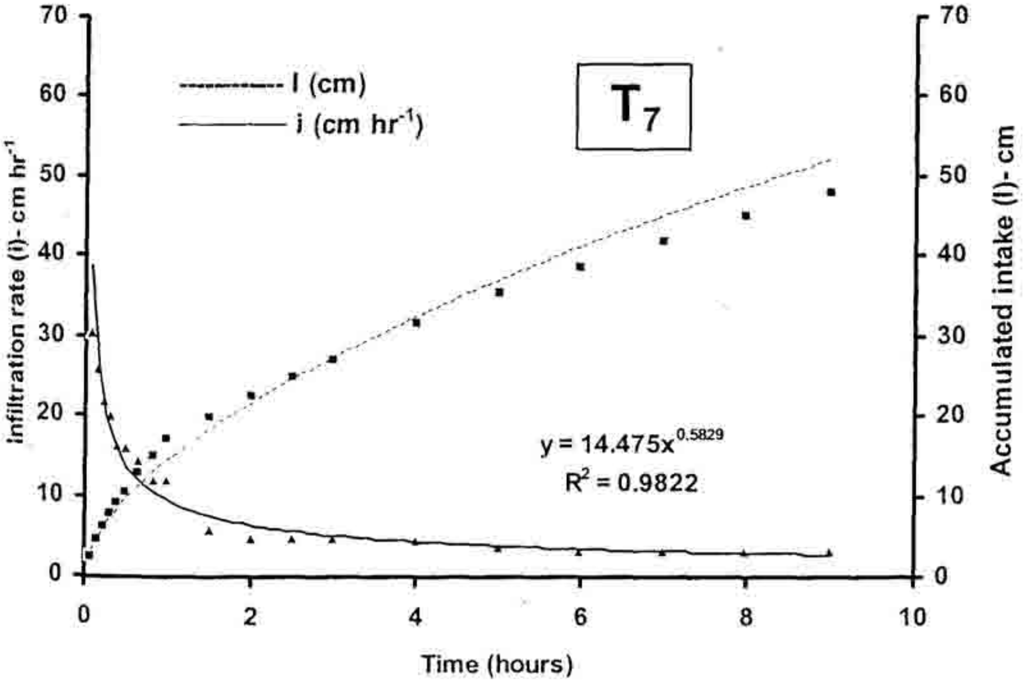


Figure 4.93: Infiltration-time curve under tillage treatment T_7 at post harvest of second wheat crop season (2003- 04)

hours depending upon the different tillage treatments.

The data on infiltration rate and cumulative infiltration were fitted to the equation of the type $I = at^b$, and are given in Table 4.2 and 4.3 for 2002-03 and 2003-04, respectively. A perusal of data in Table 4.2 showed that the value of 'a' during first year of the wheat study was higher under T_4 and T_7 and minimum in T_1 treatment following the trend $T_4 > T_7 > T_3 > T_6 > T_2 > T_5 > T_1$, respectively.

Table 4.2: Empirical equations of cumulative intake and infiltration rate under different tillage treatments at post harvest of first wheat crop season (2002-03)

Treatments*	Accumulative Intake (cm)	Infiltration rate (cm hr^{-1})	R^2
T_1	$I = 5.90t^{0.55}$	$i = dI/dt = 2.80t^{-0.45}$	0.9845
T_2	$I = 9.03t^{0.55}$	$i = dI/dt = 4.97t^{-0.45}$	0.9834
T_3	$I = 12.81t^{0.65}$	$i = dI/dt = 8.33t^{-0.35}$	0.9884
T_4	$I = 15.28t^{0.64}$	$i = dI/dt = 9.78t^{-0.36}$	0.9962
T_5	$I = 8.42t^{0.55}$	$i = dI/dt = 4.63t^{-0.45}$	0.9796
T_6	$I = 12.73t^{0.62}$	$i = dI/dt = 7.89t^{-0.38}$	0.9902
T_7	$I = 16.10t^{0.62}$	$i = dI/dt = 9.98t^{-0.38}$	0.9954

***T_1 – No tillage; T_2 – Tillage upto 10 cm depth; T_3 – Tillage upto 20 cm depth; T_4 – Tillage upto 40 cm depth; T_5 – Tillage upto 10 cm depth; T_6 – Tillage upto 20 cm depth and T_7 – Tillage upto 40 cm depth**

It is evident from Table 4.3 that the value of 'a' during second year of the wheat study was higher under T_4 and minimum in T_1 treatment following the trend $T_4 > T_7 > T_3 > T_2 > T_6 > T_5 > T_1$, respectively.

Table 4.3: Empirical equations of cumulative intake and infiltration rate under different tillage treatments at post harvest of second wheat crop season (2003-04)

Treatments*	Accumulative Intake (cm)	Infiltration rate (cm hr^{-1})	R^2
T_1	$I = 7.05t^{0.55}$	$i = dI/dt = 3.89t^{-0.44}$	0.9830
T_2	$I = 10.38t^{0.52}$	$i = dI/dt = 5.40t^{-0.48}$	0.9797
T_3	$I = 14.12t^{0.60}$	$i = dI/dt = 8.47t^{-0.40}$	0.9863
T_4	$I = 16.71t^{0.61}$	$i = dI/dt = 10.19t^{-0.39}$	0.9952
T_5	$I = 8.37t^{0.56}$	$i = dI/dt = 4.69t^{-0.44}$	0.9835
T_6	$I = 9.48t^{0.58}$	$i = dI/dt = 5.50t^{-0.42}$	0.9939
T_7	$I = 14.48t^{0.58}$	$i = dI/dt = 8.40t^{-0.42}$	0.9822

***T_1 – No tillage; T_2 – Tillage upto 10 cm depth; T_3 – Tillage upto 20 cm depth; T_4 – Tillage upto 40 cm depth; T_5 – No tillage; T_6 – No tillage and T_7 – No tillage**

4.3.3 Mechanical properties

4.3.3.1 Energy required for land preparation

The plots were dug and pulverized manually one month and fifteen days after rice harvest for sowing of wheat during 2002 and 2003, respectively. The energy required for land preparation during both years of wheat study was higher under T_4 as compared to all of the other treatments. The energy required for land preparation during first year of the study (Figure 4.94) increased significantly from 1.97 GJ ha^{-1} in treatment T_2, to T_3 (5.16 GJ ha^{-1}) and T_4 (10.01 GJ ha^{-1}). Similarly, the energy required for land preparation increased significantly from 1.67 GJ ha^{-1} in treatment T_2, to T_3 (4.21 GJ ha^{-1}) and T_4 (8.67 GJ ha^{-1}) during second year of wheat growing season.

4.3.4 Soil temperature

The weekly soil temperature measured twice a day at 0.05 and 0.1 m depth i.e. at 0630 and 1430 hours during the first and second wheat crop season are

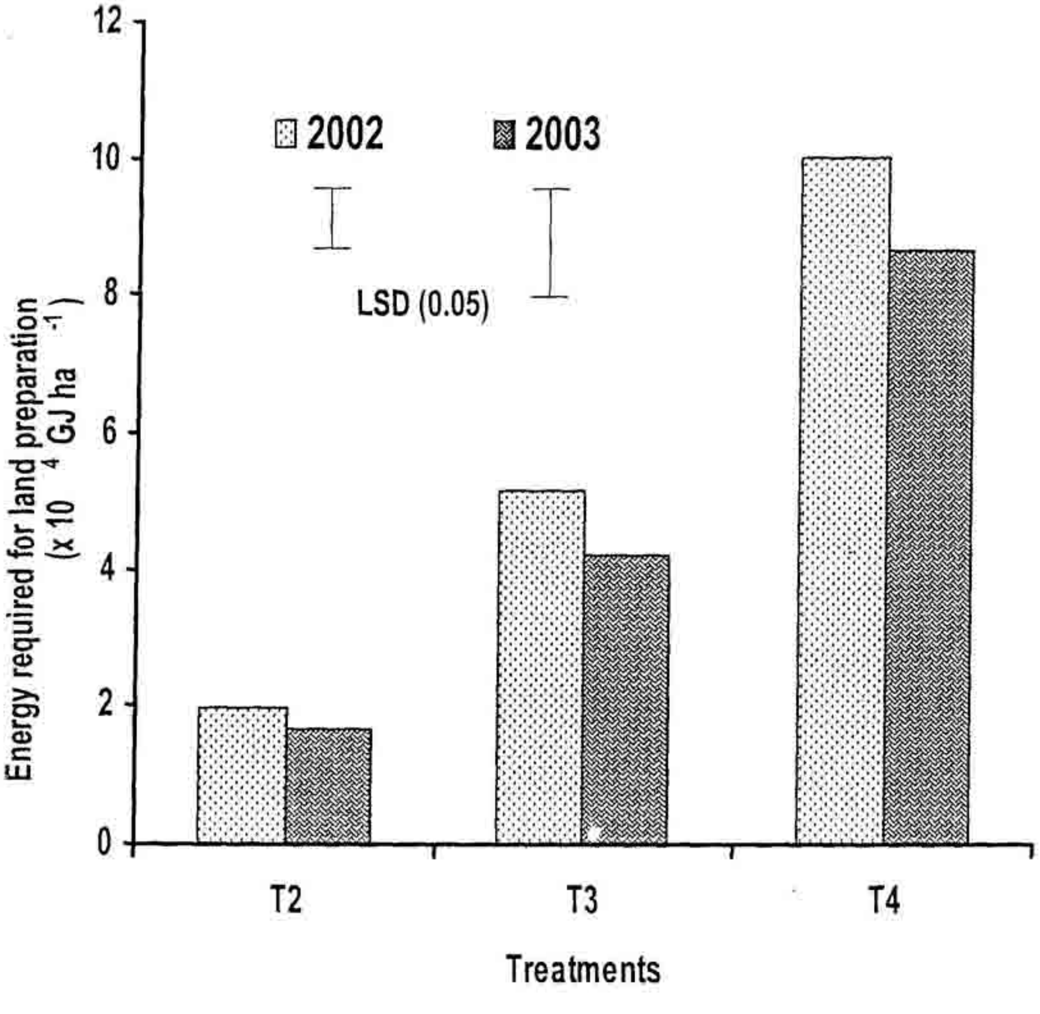


Figure 4.94: Energy required for land preparation under different tillage treatments for the first and second wheat crop season

shown in Figure 4.95, 4.96, 4.97 and 4.98 (2002-03), and 4.99, 4.100, 4.101 and 4.102 (2003-04), respectively. The daily data were averaged into weekly values. The soil temperature under all the treatments was less at 0630 than 1430 hours. The difference in soil temperature between 0630 and 1430 hours was more during cold periods and this difference became narrow as the warm period progressed. An examination of figure indicates that at 0630 hours, the soil temperature in 0.1 m soil depth was higher as compared to 0.05 m soil depth and the soil temperature was higher in 0.05 m soil depth than 0.1 m at 1430 hours in all the seven tillage treatments (T_1, T_2, T_3, T_4, T_5, T_6 and T_7) during 2002-03 and 2003-04. The treatments T_4 and T_7 had 0.5 to 1.3^{0}C and 0.3 to 1.4^{0}C higher minimum temperature at 0630 hours and 0.5 to 1.6^{0}C and 0.5 to 1.7^{0}C lower maximum temperature at 1430 hours compared to T_1 in 0.05 m soil depth during 2002-03 (Figure 4.95 and 4.97), whereas in 0.1 m soil depth, the T_4 and T_7 had 0.2 to 1.6^{0}C and 0.4 to 1.6^{0}C higher minimum temperature at 0630 hours and 0.4 to 1.7^{0}C and 0.4 to 1.8^{0}C lower maximum temperature at 1430 hours compared to T_1 during 2002-03 (Figure 4.96 and 4.98), respectively. The corresponding values during 2003-04 for minimum temperature were 0.4 to 1.3^{0}C and 0.1 to 0.6^{0}C and for maximum temperature were 0.1 to 2.7^{0}C and 0.1 to 0.9^{0}C under T_4 and T_7 as compared to T_1 treatment in 0.05 m soil depth (Figure 4.99 and 4.101), whereas in 0.1 m soil depth, the values for minimum temperature were 0.2 to 1.7^{0}C and 0.1 to 1.1^{0}C and for maximum temperature were 0.5 to 2.5^{0}C and 0.1 to 1.1^{0}C under T_4 and T_7 as compared to T_1 treatment in 0.05 m soil depth (Figure 4.100 and 4.102), respectively.

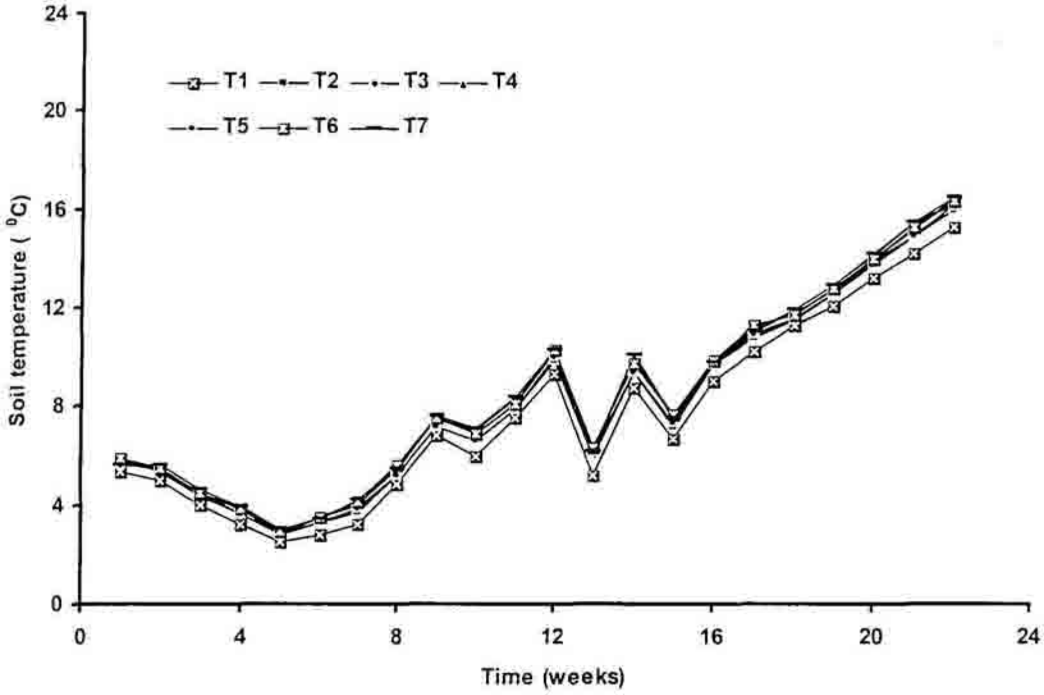


Figure 4.95: Mean weekly temperature variations at 0.05 m soil depth under different tillage treatments for the first wheat crop season (2002-03), at 0630 hours

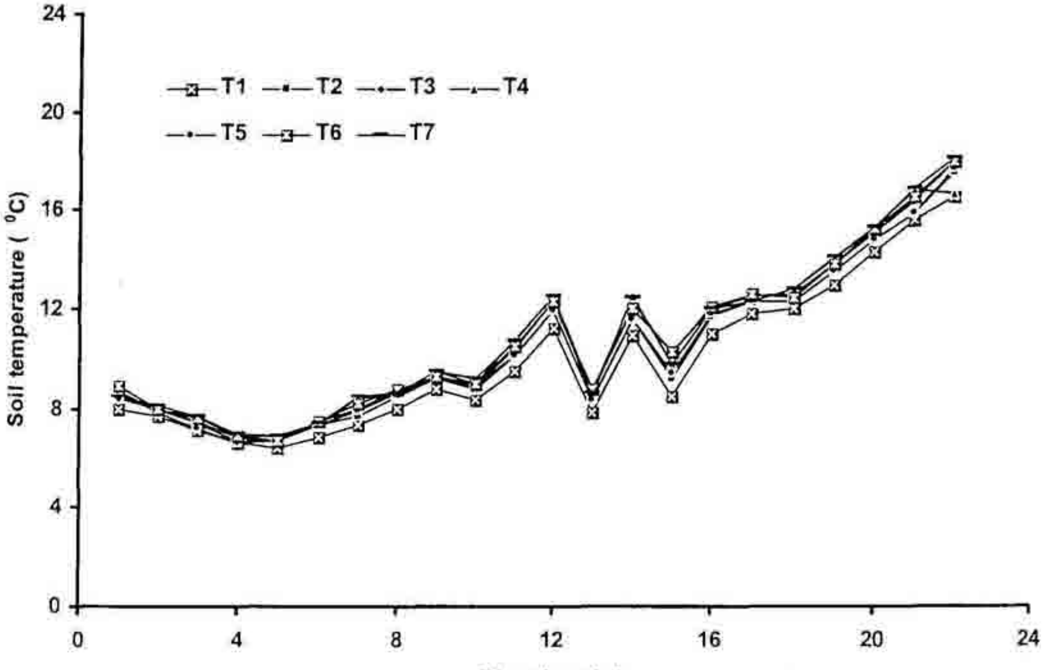


Figure 4.96: Mean weekly temperature variations at 0.1 m soil depth under different tillage treatments for the first wheat crop season (2002-03), at 0630 hours

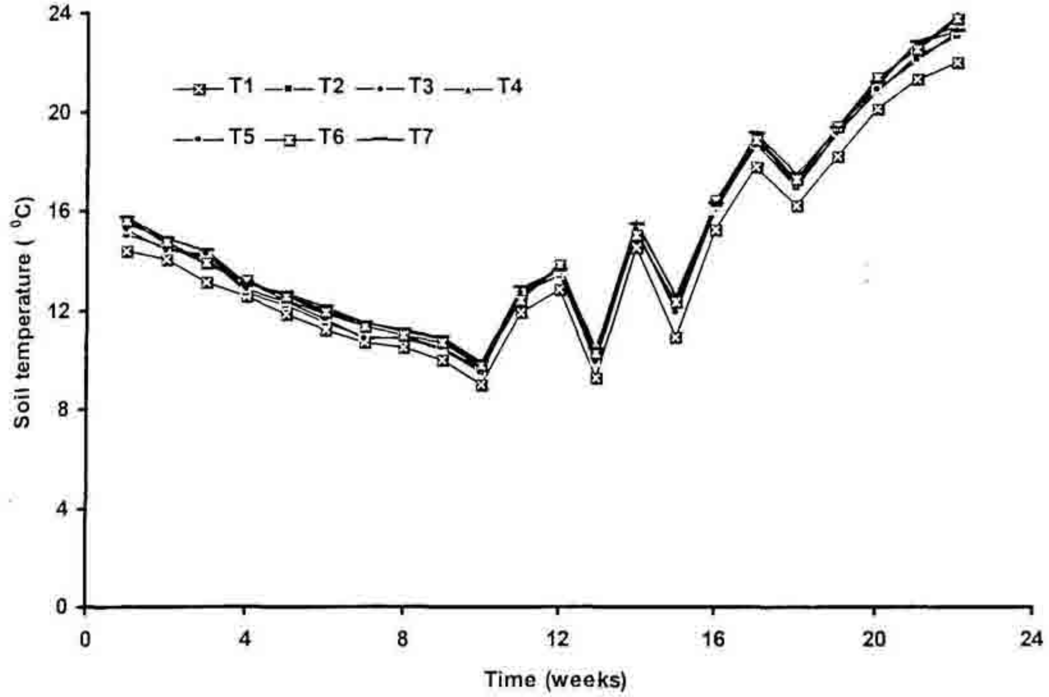


Figure 4.97: Mean weekly temperature variations at 0.05 m soil depth under different tillage treatments for the first wheat crop season (2002-03), at 1430 hours

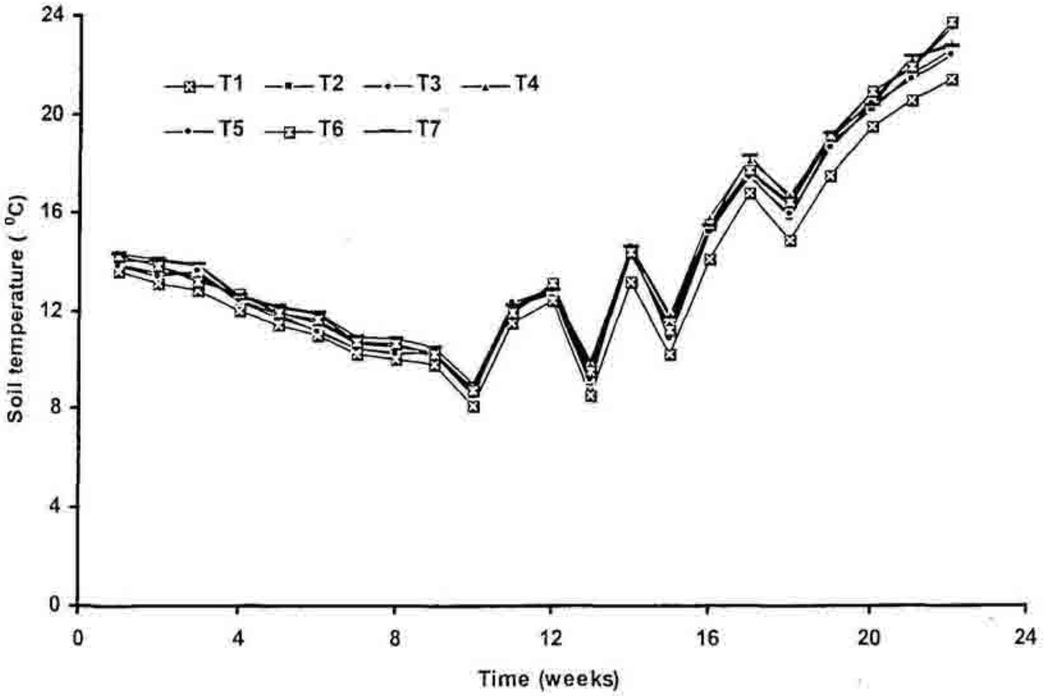


Figure 4.98: Mean weekly temperature variations at 0.1 m soil depth under different tillage treatments for the first wheat crop season (2002-03), at 1430 hours

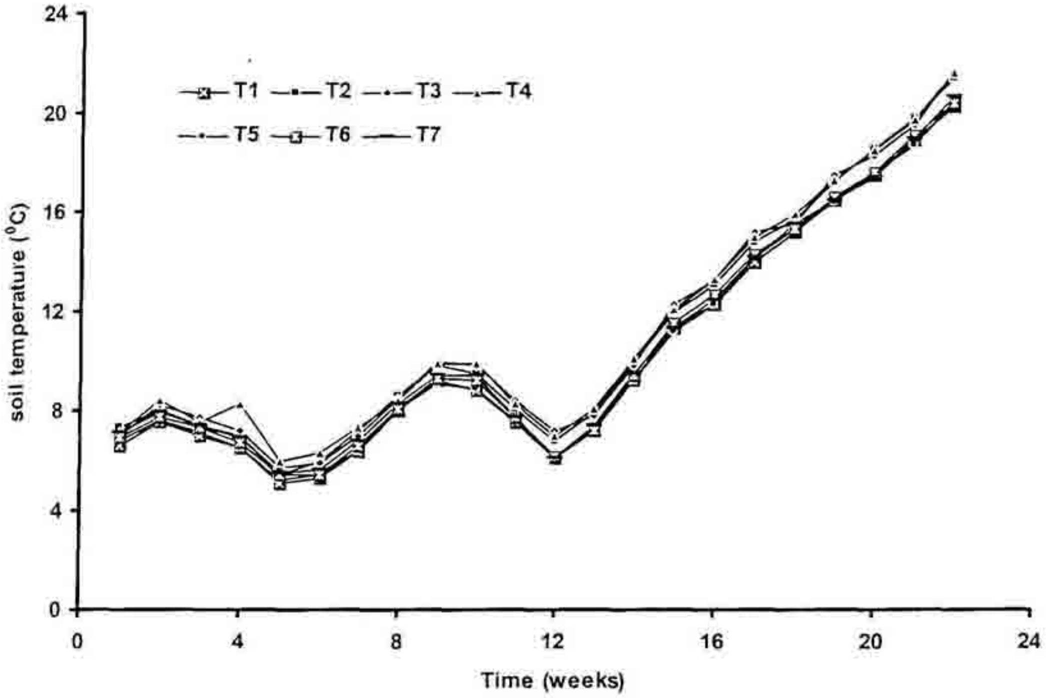


Figure 4.99: Mean weekly temperature variations at 0.05 m soil depth under different tillage treatments for the second wheat crop season (2003- 04), at 0630 hours

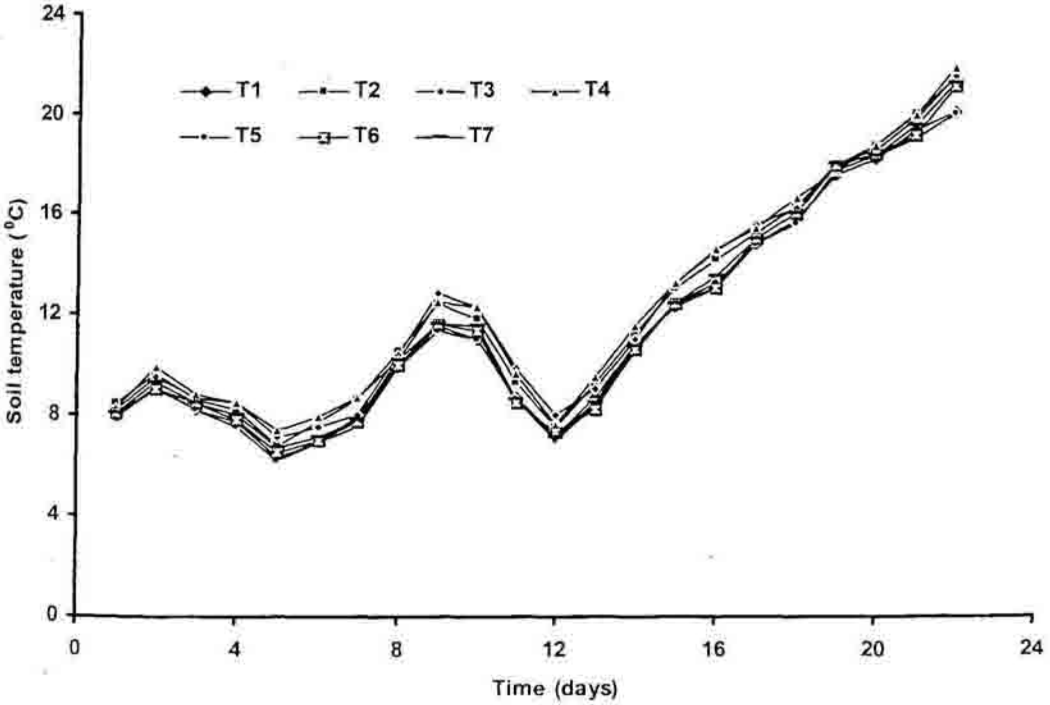


Figure 4.100: Mean weekly temperature variations at 0.1 m soil depth under different tillage treatments for the second wheat crop season (2003- 04), at 0630 hours

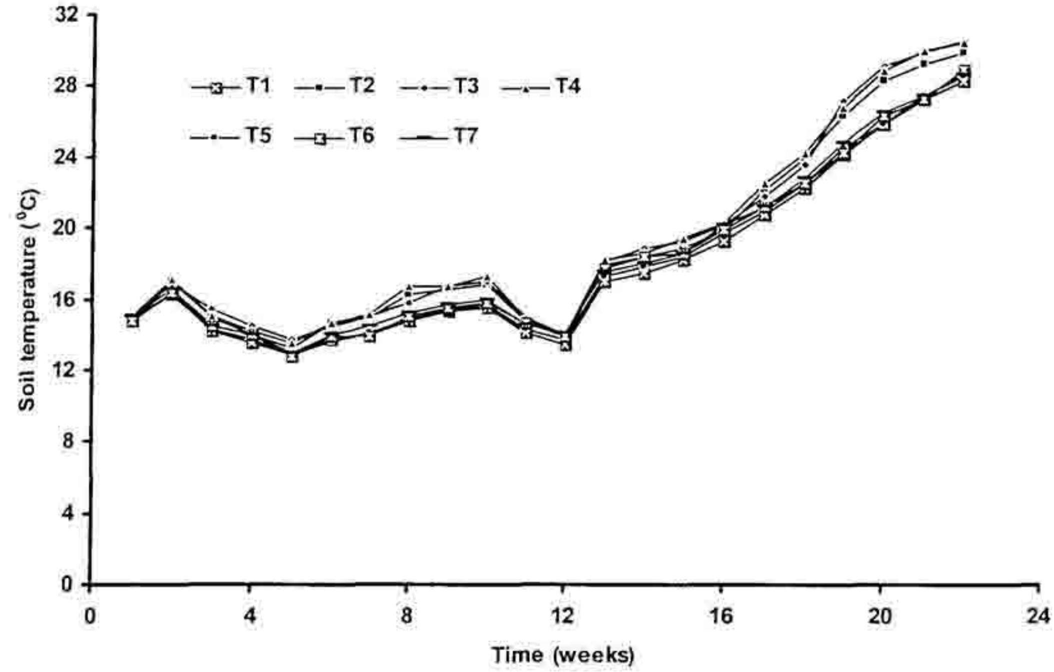


Figure 4.101: Mean weekly temperature variations at 0.05 m soil depth under different tillage treatments for the second wheat crop season (2003- 04), at 1430 hours

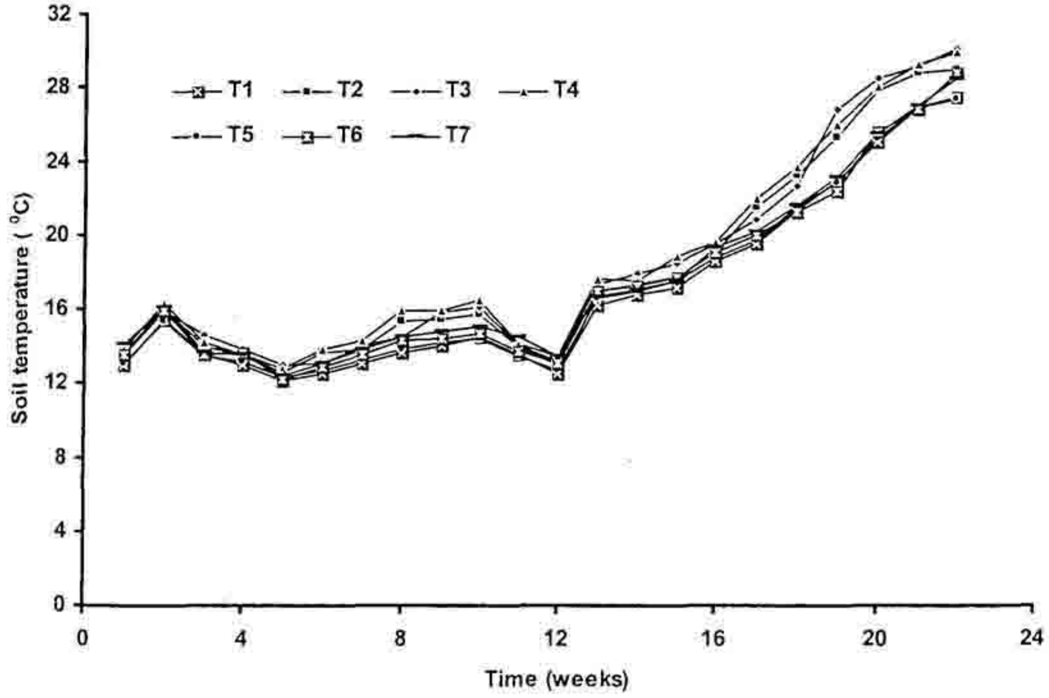


Figure 4.102: Mean weekly temperature variations at 0.1 m soil depth under different tillage treatments for the second wheat crop season (2003- 04), at 1430 hours

4.4 Plant observations

4.4.1 Plant growth parameters

4.4.1.1 Emergence count

An observation of data on emergence count per m^2 of wheat as influenced by different treatments revealed that during *Rabi* season of 2002-03 and 2003-04, tillage at different depths had significant influence on the emergence count have been presented in Table 4.4 and 4.5. A perusal of the data in Table 4.4 reported that during 2002-03, emergence count per m^2 was statistically at par in treatments T_4 and T_7 but was significantly higher as compared to T_1, T_2, T_3, T_5 and T_6, respectively.

Table 4.4: Emergence count under different tillage treatments for the first wheat crop season (2002-03)

Treatments*	Emergence count (m^{-2})
T_1	156.00
T_2	168.67
T_3	181.67
T_4	194.33
T_5	169.67
T_6	180.67
T_7	193.33
LSD (0.05)	**10.05**

***T_1 – No tillage; T_2 – Tillage upto 10 cm depth; T_3 – Tillage upto 20 cm depth; T_4 – Tillage upto 40 cm depth; T_5 – Tillage upto 10 cm depth; T_6 – Tillage upto 20 cm depth and T_7 – Tillage upto 40 cm depth**

During second wheat crop season (2003-04), the emergence count per m^2 was significantly higher in treatment T_4 as compared to all the other treatments (Table 4.5). The next higher was T_7 which was statistically at par with treatment T_3, but significantly different from T_1, T_2, T_5 and T_6, respectively. In both the years of study, the treatments T_4 and T_7 showed higher wheat emergence count per m^2 as compared to all the other treatments. The lowest emergence count per m^2 was, however, observed in T_1 in both the years of crop study.

Table 4.5: Emergence count under different tillage treatments for the second wheat crop season (2003-04)

Treatments*	Emergence count (m^{-2})
T_1	156.67
T_2	171.00
T_3	185.00
T_4	198.33
T_5	166.33
T_6	174.33
T_7	181.00
LSD (0.05)	**5.86**

***T_1 – No tillage; T_2 – Tillage upto 10 cm depth; T_3 – Tillage upto 20 cm depth; T_4 – Tillage upto 40 cm depth; T_5 – No tillage; T_6 – No tillage and T_7 – No tillage**

4.4.1.2 Seedling emergence parameters

The seedling emergence parameters *viz.* initiation of emergence (days), days for attaining constant emergence and emergence velocity (% day^{-1}) recorded during both (2002-03 and 2003-04) crop seasons are presented in Table 4.6 and 4.7, respectively. The seedling emergence parameters were significantly affected by the different tillage treatments (T_1, T_2, T_3, T_4, T_5, T_6 and T_7) in both wheat crop seasons.

4.4.1.2.1 Initiation of emergence

During the first year of the study (2002-03), significantly higher days to initiation of emergence (12.7 days) were taken under T_1 compared to all the other treatments (Table 4.6). Treatments T_3, T_4, T_6 and T_7 were statistically at par and days to initiation of germination under the treatments were comparatively less.

Table 4.6: Seedling emergence parameters under different tillage treatments for the first wheat crop season (2002-03)

Treatments*	Initiation of Emergence (days)	Constant Emergence (days)	Emergence (%)	#Emergence Velocity (% per day)
T_1	12.7	25.7	70.7	2.75
T_2	11.0	23.0	78.0	3.40
T_3	9.3	21.7	84.0	3.88
T_4	8.3	18.7	90.0	4.82
T_5	10.7	22.0	77.7	3.53
T_6	9.0	21.0	84.0	4.01
T_7	8.7	18.0	89.7	4.99
LSD (0.05)	**1.3**	**1.3**	**1.8**	**0.3**

***T_1 – No tillage; T_2 – Tillage upto 10 cm depth; T_3 – Tillage upto 20 cm depth; T_4 – Tillage upto 40 cm depth; T_5 – Tillage upto 10 cm depth; T_6 – Tillage upto 20 cm depth and T_7 – Tillage upto 40 cm depth**

$$\text{\# Emergence Velocity (\% per day)} = \frac{\text{Emergence (\%)}}{\text{Days to constant emergence}}$$

The number of days taken for initiation of emergence during the second year of the study (2003-04) was statistically less under treatment T_4 (7.7days) as compared to T_1, T_2, T_5, T_6, and T_7 (13.7, 10.7, 12.0, 10.3 and 9.3 days) treatments, but was statistically at par with T_3 (8.7 days). Similar to first year study, the significantly highest days to initiation of emergence (13.7 days) were taken by T_1 and significantly lowest under T_4 (7.7days) treatment. The treatment T_7 had taken significantly less time for initiation of emergence as compared to T_1, T_2 and T_3 (Table 4.7).

Table 4.7: **Seedling emergence parameters under different tillage treatments for the second wheat crop season (2003-04)**

Treatments*	Initiation of Emergence (days)	Constant Emergence (days)	Emergence (%)	Emergence Velocity (% per day)
T_1	13.7	25.3	72.3	2.86
T_2	10.7	22.7	79.0	3.49
T_3	8.7	20.7	85.0	4.12
T_4	7.7	18.0	92.3	5.13
T_5	12.0	24.0	74.7	3.11
T_6	10.3	22.0	78.0	3.55
T_7	9.3	20.3	80.7	3.79
LSD (0.05)	**1.3**	**1.0**	**1.2**	**0.1**

***T_1 – No tillage; T_2 – Tillage upto 10 cm depth; T_3 – Tillage upto 20 cm depth; T_4 – Tillage upto 40 cm depth; T_5 – No tillage; T_6 – No tillage and T_7 – No tillage**

4.4.1.2.2 Seedling constant emergence

A perusal of the data in Table 4.6 indicated that during the first year of the study the number of days taken to attain constant emergence were lowest under T_4 (18.7) and were significantly lower as compared to T_1, T_2, T_3, T_5 and T_6 (25.7, 23.0, 21.7, 22.0 and 21.0), however, T_4 was statistically at par with T_7 (18.0 days).

During second year of the study, the number of days taken to attain constant emergence was significantly less under treatment T_4 (18.0 day) as compared to T_1, T_2, T_3, T_5 T_6 and T_7 as given in Table 4.7. The next higher was T_7 (at par with T_3) and significantly different from T_1, T_2, T_5 and T_6, respectively. The trend during both the year of the study was almost similar.

4.4.1.2.3 Seedling emergence

The percentage of seedling emergence during first year of the study was significantly higher under treatments T_4 and T_7 (90.0 and 89.7%) as compared to T_1, T_2, T_3, T_5 and T_6 (70.7, 78.0, 84.0, 77.7, and 84.0%); T_4 and T_7 remained statistically at par (Table 4.6).

During second year of the study, the percentage of seedling emergence was significantly higher under T_4 (92.3%) as compared to T_1, T_2, T_3, T_5, T_6, and T_7 (72.3, 79.0, 85.0, 74.7, 78.0, and 80.7%), whereas T_7 had significantly higher percentage of seedling emergence as compared to T_1, T_2, T_5 and T_6 as given in Table 4.7. During both the years of the study, T_4 had the highest and T_1 had the lowest emergence percentage, but T_4 and T_7 treatments were statistically at par.

4.4.1.2.4 Emergence velocity

A perusal of the data in Table 4.6 revealed that the emergence velocity was significantly higher under treatment T_4 (4.82 % day^{-1}) as compared to T_1, T_2, T_3, T_5 and T_6 (2.75, 3.40, 3.88, 3.53, and 4.01 % day^{-1}), while treatments T_4 and T_7 remained statistically at par.

During second year of the study, the emergence velocity was significantly higher under treatment T_4 (5.13 % day^{-1}) as compared to T_1, T_2, T_3, T_5, T_6, and T_7 (2.86, 3.49, 4.12, 3.11 3.55, and 3.79 % day^{-1}); T_1 regarded the lowest emergence velocity (Table 4.7). The next higher was T_7 which was significantly different from T_1, T_2, T_5 and T_6, respectively.

4.4.1.3 Plant height

For the first year of the study, the plant height under different tillage treatments is presented in Table 4.8. At all the data of measurements for 30, 60, 90, 120 and 150 DAS (it is the characteristic of the variety that the plant height keeps on increasing even until 150 days); T_4 had the maximum whereas T_1 had the minimum plant height. Significantly higher plant height was observed at all the observation data under T_4 as compared to all the other treatments except T_7 (which was at par with T_4).

Table 4.8: Plant height (cm) under different tillage treatments for the first wheat crop season (2002-03)

Treatments*	30 DAS	60 DAS	90 DAS	120 DAS	150 DAS
T_1	12.30	23.40	43.83	73.10	89.60
T_2	13.07	25.37	47.16	76.20	94.37
T_3	13.80	27.37	50.00	78.87	99.20
T_4	14.50	29.07	53.73	83.40	104.83
T_5	13.30	25.73	48.06	76.17	95.30
T_6	14.20	27.70	50.57	79.73	99.57
T_7	14.93	29.36	54.60	84.93	105.33
LSD (0.05)	**0.46**	**1.49**	**1.85**	**1.98**	**2.50**

***T_1 – No tillage; T_2 – Tillage upto 10 cm depth; T_3 – Tillage upto 20 cm depth; T_4 – Tillage upto 40 cm depth; T_5 – Tillage upto 10 cm depth; T_6 – Tillage upto 20 cm depth and T_7 – Tillage upto 40 cm depth**

During second wheat crop season (2003-04), the plant height was significantly higher in treatment T_4 as compared to T_1, T_2, T_3, T_5, T_6, and T_7, at all stages of observations (Table 4.9). In 30, 90 and 150 DAS, treatment T_7 had significantly higher plant height as compared to T_1 and T_5, which remained statistically at par with T_2, T_3 and T_6. The treatment T_7 in 60 and 120 DAS had significantly higher plant height as compared to T_1, T_5 and T_6, but remained statistically at par with T_2 and T_3.

Table 4.9: Plant height (cm) under different tillage treatments for the second wheat crop season (2003-04)

Treatments*	30 DAS	60 DAS	90 DAS	120 DAS	150 DAS
T_1	13.33	24.33	44.10	73.63	90.60
T_2	14.03	26.53	47.77	77.13	95.30
T_3	14.70	27.73	51.83	80.03	100.17
T_4	15.37	29.20	55.13	84.23	106.13
T_5	13.53	25.17	45.67	75.30	91.57
T_6	14.00	25.80	48.77	76.40	93.83
T_7	14.37	27.00	50.33	78.77	95.13
LSD (0.05)	**0.52**	**1.10**	**2.92**	**1.70**	**2.65**

***T_1 – No tillage; T_2 – Tillage upto 10 cm depth; T_3 – Tillage upto 20 cm depth; T_4 – Tillage upto 40 cm depth; T_5 – No tillage; T_6 – No tillage and T_7 – No tillage**

4.4.1.4 Number of tillers

The effect of different tillage treatments on number of tillers per m^2 of wheat is presented in Table 4.10 and 4.11, respectively. It is evident from Table 4.10 that for the first year of the study, a progressive increase in tiller count per m^2 was observed upto 90 days of wheat sowing in all the tillage treatments. At 30, 60 and 90 DAS, the number of tillers per m^2 was statistically at par between treatments T_4 and T_7 but was significantly higher compared to T_1, T_2, T_3, T_5 and T_6.

During second wheat crop season (2003-04), the number of tillers per m^2 was significantly higher in treatment T_4 as compared to T_1, T_2, T_3, T_5, T_6, and T_7 in 30, 60 and 90 DAS (Table 4.11). In 30 DAS, T_7 had significantly higher number of tillers per m^2 as compared to T_1, T_2, T_5, and T_6, which remained statistically at par with treatment T_3 at all stages of observations, respectively. Similar trend was observed in 60 and 90 DAS of wheat plant.

Table 4.10: Number of tillers (m^{-2}) under different tillage treatments for the first wheat crop season (2002-03)

Treatments*	30 DAS	60 DAS	90 DAS
T_1	197.0	274.7	352.3
T_2	214.0	307.3	401.0
T_3	234.7	350.0	446.0
T_4	254.7	379.0	491.7
T_5	215.7	315.7	417.7
T_6	234.0	356.0	453.7
T_7	255.0	387.3	495.0
LSD (0.05)	**16.0**	**14.0**	**13.9**

***T_1 – No tillage; T_2 – Tillage upto 10 cm depth; T_3 – Tillage upto 20 cm depth; T_4 – Tillage upto 40 cm depth; T_5 – Tillage upto 10 cm depth; T_6 – Tillage upto 20 cm depth and T_7 – Tillage upto 40 cm depth**

Table 4.11: Number of tillers (m^{-2}) under different tillage treatments for the second wheat crop season (2003-04)

Treatments*	30 DAS	60 DAS	90 DAS
T_1	198.3	279.0	373.7
T_2	216.7	311.3	413.7
T_3	236.3	352.7	452.7
T_4	259.7	383.3	507.3
T_5	209.7	292.0	388.0
T_6	224.0	303.7	412.0
T_7	234.3	339.3	443.7
LSD (0.05)	**13.1**	**14.8**	**11.6**

***T_1 – No tillage; T_2 – Tillage upto 10 cm depth; T_3 – Tillage upto 20 cm depth; T_4 – Tillage upto 40 cm depth; T_5 – No tillage; T_6 – No tillage and T_7 – No tillage**

4.4.1.5 Dry matter accumulation

The effects of different treatments on dry matter accumulation for two year of study i.e. 2002-03 and 2003-04 have been presented in Table 4.12 and 4.13, respectively. A study of data during first wheat crop season in Table 4.12 revealed that in general, tillage treatments significantly influenced the dry matter accumulation of wheat at all stages of observations i.e. 30, 60, 90, 120 and 150 DAS. An examination of data showed that dry matter accumulation was significantly higher in treatment T_4 (statistically at par with T_7) as compared to T_1, T_2, T_3, T_5 and T_6 at all the stages of observations. Other treatments were intermediate.

Table 4.12: Dry matter accumulation (g m^{-2}) under different tillage treatments for the first wheat crop season (2002-03)

Treatments*	30 DAS	60 DAS	90 DAS	120 DAS	150 DAS
T_1	3.57	29.56	261.23	474.19	597.93
T_2	5.01	43.52	411.43	673.31	776.37
T_3	6.06	78.98	611.44	831.81	977.47
T_4	7.89	99.27	869.67	946.66	1124.73
T_5	5.00	43.23	402.01	672.38	775.12
T_6	6.16	78.12	589.18	824.49	955.42
T_7	7.89	98.36	888.18	956.77	1119.48
LSD (0.05)	**0.50**	**4.24**	**28.78**	**34.10**	**36.03**

***T_1 – No tillage; T_2 – Tillage upto 10 cm depth; T_3 – Tillage upto 20 cm depth; T_4 – Tillage upto 40 cm depth; T_5 – Tillage upto 10 cm depth; T_6 – Tillage upto 20 cm depth and T_7 – Tillage upto 40 cm depth**

The dry matter accumulation during second year of the study was significantly higher in treatment T_4 as compared to T_1, T_2, T_3, T_5, T_6, and T_7 in 30, 60, 90, 120 and 150 DAS (Table 4.13). At all the stages of observations, treatment T_7 had significantly higher dry matter accumulation as compared to T_1, T_2, T_5, and T_6, which remained statistically at par with treatment T_3, respectively. The dry matter accumulation was, however, observed in T_1 and highest in T_4 treatment in both the years of crop study.

Table 4.13: Dry matter accumulation (g m^{-2}) under different tillage treatments for the second wheat crop season (2003-04)

Treatments*	30 DAS	60 DAS	90 DAS	120 DAS	150 DAS
T_1	4.02	31.92	282.08	497.27	641.74
T_2	5.21	46.26	422.23	619.96	792.04
T_3	6.38	83.96	612.49	820.22	991.59
T_4	8.24	104.89	907.73	1009.44	1247.70
T_5	4.41	39.76	338.98	592.38	700.37
T_6	4.87	56.46	480.76	728.91	860.63
T_7	5.71	71.35	599.67	801.93	978.86
LSD (0.05)	**0.27**	**4.63**	**23.88**	**26.64**	**23.52**

***T_1 – No tillage; T_2 – Tillage upto 10 cm depth; T_3 – Tillage upto 20 cm depth; T_4 – Tillage upto 40 cm depth; T_5 – No tillage; T_6 – No tillage and T_7 – No tillage**

4.4.2 Leaf water potential

Leaf water potential values determined at crown root initiation and flowering stage of both the years of wheat crop during 2002-03 and 2003-04 on selected days at 1200 hour have been shown in Table 4.14 and 4.15. Data indicated that leaf water potential during both the years of the study period was non-significant in all the tillage treatments at crown root initiation and flowering stage. No discernable difference among different treatment was observed.

Table 4.14: Leaf water potential (12 noon) at crown root initiation and flowering stage under different tillage treatments for the first wheat crop season (2002-03)

Treatments*	Leaf water potential (-kPa)	
	Crown root initiation	Flowering stage
T_1	3113	2267
T_2	3133	2253
T_3	3100	2260
T_4	3123	2246
T_5	3120	2270
T_6	3130	2257
T_7	3113	2253
LSD (0.05)	**NS**	**NS**

*T_1 – No tillage; T_2 – Tillage upto 10 cm depth; T_3 – Tillage upto 20 cm depth; T_4 – Tillage upto 40 cm depth; T_5 – Tillage upto 10 cm depth; T_6 – Tillage upto 20 cm depth and T_7 – Tillage upto 40 cm depth

Table 4.15: Leaf water potential (12 noon) at crown root initiation and flowering stage under different tillage treatments for the second wheat crop season (2003-04)

Treatments*	Leaf water potential (-kPa)	
	Crown root initiation	Flowering stage
T_1	3340	2353
T_2	3347	2360
T_3	3337	2363
T_4	3323	2357
T_5	3333	2373
T_6	3343	2343
T_7	3340	2367
LSD (0.05)	**NS**	**NS**

*T_1 – No tillage; T_2 – Tillage upto 10 cm depth; T_3 – Tillage upto 20 cm depth; T_4 – Tillage upto 40 cm depth; T_5 – No tillage; T_6 – No tillage and T_7 – No tillage

4.4.3 Root studies

4.4.3.1 Root mass density (RMD)

The effect of different tillage treatments on root mass density (RMD) values of wheat is presented in Table 4.16 and 4.17 for 2002-03 and 2003-04, respectively. A perusal of data presented in Table 4.16 indicated that during 2002-03, the RMD values for T_4 (at par with T_7) on 30, 60 and 90 DAS were significantly higher than T_1, T_2, T_3, T_5 and T_6, respectively.

Table 4.16: Root mass density (kg m^{-3}) under different tillage treatments at 0.0-0.1 m soil depth for the first wheat crop season (2002-03)

Treatments*	30 DAS	60 DAS	90 DAS
T_1	0.024	0.153	0.354
T_2	0.032	0.234	0.536
T_3	0.039	0.334	0.680
T_4	0.049	0.433	0.875
T_5	0.033	0.235	0.586
T_6	0.040	0.351	0.677
T_7	0.048	0.463	0.847
LSD (0.05)	**0.005**	**0.058**	**0.107**

***T_1 – No tillage; T_2 – Tillage upto 10 cm depth; T_3 – Tillage upto 20 cm depth; T_4 – Tillage upto 40 cm depth; T_5 – Tillage upto 10 cm depth; T_6 – Tillage upto 20 cm depth and T_7 – Tillage upto 40 cm depth**

During the second year of the study (2003-04), the RMD values (30, 60 and 90 DAS) were significantly higher in treatment T_4 as compared to all the other treatments (Table 4.17). The next higher was T_7 which was statistically at par with treatment T_3, but significantly different from T_1, T_2, T_5 and T_6. In both the years of study, the treatments T_4 and T_7 showed higher RMD values as compared to all the other treatments. The lowest RMD value was, however, observed in T_1 in both the years of study.

Table 4.17: Root mass density (kg m^{-3}) under different tillage treatments at 0.0-0.1 m soil depth for the second wheat crop season (2003-04)

Treatments*	30 DAS	60 DAS	90 DAS
T_1	0.025	0.171	0.373
T_2	0.33	0.259	0.570
T_3	0.040	0.363	0.715
T_4	0.049	0.458	0.922
T_5	0.028	0.190	0.406
T_6	0.030	0.249	0.534
T_7	0.038	0.375	0.691
LSD (0.05)	**0.003**	**0.073**	**0.112**

***T_1 – No tillage; T_2 – Tillage upto 10 cm depth; T_3 – Tillage upto 20 cm depth; T_4 – Tillage upto 40 cm depth; T_5 – No tillage; T_6 – No tillage and T_7 – No tillage**

The depth-wise RMD values under different tillage treatments were also determined at 120 and 150 DAS in two wheat seasons during 2002-03 and 2003-04 (Table 4.18 and 4.19). In both the years of study, RMD value decreased with soil depth. A perusal of the data in Table 4.16, also indicated that RMD values at 120 and 150 DAS in all the consecutive soil layers (0.0-0.1, 0.1-0.2 and 0.2-0.3 m) was significantly higher in T_4 as compared to T_1, T_2, T_3, T_5 and T_6, which remained statistically at par with T_7 in first year study.

The RMD values at 120 and 150 DAS during second year (2003-04) of the study were significantly higher in T_4 as compared to T_1, T_2, T_3, T_5, T_6 and T_7 in all the three consecutive soil depths (0.0-0.1, 0.1-0.2 and 0.2-0.3 m), respectively. Additionally, T_3 and T_7 (which were at par among themselves)

Table 4.18: Depth-wise root mass density (kg m^{-3}) under different tillage treatments at 120 and 150 DAS for the first wheat crop season (2002-03)

Treatments*	120 DAS			150 DAS		
	Depth (m)					
	0.0-0.1	0.1-0.2	0.2-0.3	0.0-0.1	0.1-0.2	0.2-0.3
T_1	0.924	0.155	0.048	1.320	0.246	0.064
T_2	1.233	0.217	0.064	1.617	0.331	0.082
T_3	1.490	0.263	0.104	1.923	0.419	0.140
T_4	1.826	0.406	0.141	2.387	0.539	0.185
T_5	1.251	0.207	0.068	1.544	0.319	0.080
T_6	1.462	0.272	0.114	1.893	0.403	0.145
T_7	1.804	0.391	0.152	2.362	0.578	0.190
LSD (0.05)	**0.149**	**0.041**	**0.015**	**0.153**	**0.047**	**0.032**

*T_1 – No tillage; T_2 – Tillage upto 10 cm depth; T_3 – Tillage upto 20 cm depth; T_4 – Tillage upto 40 cm depth; T_5 – Tillage upto 10 cm depth; T_6 – Tillage upto 20 cm depth and T_7 – Tillage upto 40 cm depth

Table 4.19: Depth-wise root mass density (kg m^{-3}) under different tillage treatments at 120 and 150 DAS for the second wheat crop season (2003-04)

Treatments*	120 DAS			150 DAS		
	Depth (m)					
	0.0-0.1	0.1-0.2	0.2-0.3	0.0-0.1	0.1-0.2	0.2-0.3
T_1	0.953	0.169	0.053	1.345	0.270	0.069
T_2	1.261	0.239	0.069	1.653	0.356	0.088
T_3	1.542	0.283	0.114	1.968	0.438	0.154
T_4	1.901	0.429	0.165	2.584	0.568	0.198
T_5	1.045	0.178	0.054	1.408	0.278	0.073
T_6	1.301	0.227	0.075	1.558	0.309	0.094
T_7	1.461	0.248	0.099	1.797	0.401	0.139
LSD (0.05)	**0.123**	**0.045**	**0.016**	**0.206**	**0.040**	**0.014**

*T_1 – No tillage; T_2 – Tillage upto 10 cm depth; T_3 – Tillage upto 20 cm depth; T_4 – Tillage upto 40 cm depth; T_5 – No tillage; T_6 – No tillage and T_7 – No tillage

had significantly higher RMD value as compared to T_1, T_2, T_5 and T_6 (Table 4.19).

4.4.3.2 Root length density (RLD)

The influence of different tillage treatments on RLD of wheat during 2002-03 and 2003-04 recorded at 30, 60 and 90 DAS is presented in Table 4.20 and 4.21, respectively. During 2002-03 at 30, 60 and 90 DAS, the RLD values were statistically at par in treatments T_4 and T_7 but were significantly higher as compared to T_1, T_2, T_3, T_5 and T_6, respectively (Table 4.20).

Table 4.20: Root length density (m m^{-3}) under different tillage treatments at 0.0-0.1 m soil depth for the first wheat crop season (2002-03)

Treatments*	30 DAS	60 DAS	90 DAS
T_1	0.030	0.102	0.353
T_2	0.038	0.163	0.579
T_3	0.044	0.247	0.879
T_4	0.053	0.375	1.117
T_5	0.038	0.169	0.543
T_6	0.043	0.234	0.902
T_7	0.051	0.357	1.151
LSD (0.05)	**0.005**	**0.028**	**0.135**

***T_1 – No tillage; T_2 – Tillage upto 10 cm depth; T_3 – Tillage upto 20 cm depth; T_4 – Tillage upto 40 cm depth; T_5 – Tillage upto 10 cm depth; T_6 – Tillage upto 20 cm depth and T_7 – Tillage upto 40 cm depth**

It is evident from Table 4.21 that the RLD values during second year (2003-04) of the study at 30, 60 and 90 DAS were significantly higher in T_4 as compared to T_1, T_2, T_3, T_5, T_6 and T_7 treatments. The next higher values of RLD were observed under T_7 (at par with T_3) which were significantly higher than T_1, T_2, T_5 and T_6.

Table 4.21: Root length density (m m^{-3}) under different tillage treatments at 0.0-0.1 m soil depth for the second wheat crop season (2003-04)

Treatments*	30 DAS	60 DAS	90 DAS
T_1	0.031	0.113	0.364
T_2	0.039	0.179	0.595
T_3	0.045	0.294	0.912
T_4	0.053	0.434	1.184
T_5	0.032	0.120	0.399
T_6	0.035	0.153	0.512
T_7	0.041	0.275	0.809
LSD (0.05)	**0.04**	**0.039**	**0.114**

***T_1 – No tillage; T_2 – Tillage upto 10 cm depth; T_3 – Tillage upto 20 cm depth; T_4 – Tillage upto 40 cm depth; T_5 – No tillage; T_6 – No tillage and T_7 – No tillage**

The depth-wise RLD values under different tillage treatments were also determined at 120 and 150 DAS in two wheat seasons during 2002-03 and 2003-04 (Table 4.22 and 4.23). In both the years of study, RLD values were decreased with soil depth. An examination of data in Table 4.22 showed that RLD values at 120 and 150 DAS were statistically at par in treatments T_4 and T_7 but were significantly higher as compared to T_1, T_2, T_3, T_5 and T_6 in all the soil depths (0.0-0.1, 0.1-0.2 and 0.2-0.3 m).

During second year of the study, the RLD values at 120 DAS were significantly higher in T_4 as compared to T_1, T_2, T_3, T_5, T_6 and T_7 in all the three consecutive soil depths (0.0-0.1, 0.1-0.2 and 0.2-0.3 m), respectively. The treatment T_7 (at par with T_3) had significantly higher RLD values as compared to T_1, T_2, T_5 and T_6 (Table 4.23). Similar trend was observed in RLD value on 150 DAS.

Table 4.22: Depth-wise root length density (m m^{-3}) under different tillage treatments at 120 and 150 DAS for the first wheat crop season (2002-03)

Treatments*	120 DAS			150 DAS		
	Depth (m)					
	0.0-0.1	**0.1-0.2**	**0.2-0.3**	**0.0-0.1**	**0.1-0.2**	**0.2-0.3**
T_1	0.758	0.210	0.052	1.078	0.291	0.070
T_2	1.017	0.253	0.065	1.468	0.362	0.095
T_3	1.260	0.308	0.111	1.839	0.450	0.152
T_4	1.794	0.424	0.154	2.316	0.561	0.201
T_5	0.989	0.258	0.069	1.538	0.372	0.091
T_6	1.304	0.297	0.105	1.914	0.463	0.160
T_7	1.759	0.411	0.153	2.283	0.554	0.204
LSD (0.05)	**0.207**	**0.043**	**0.012**	**0.188**	**0.026**	**0.021**

*T_1 – No tillage; T_2 – Tillage upto 10 cm depth; T_3 – Tillage upto 20 cm depth; T_4 – Tillage upto 40 cm depth; T_5 – Tillage upto 10 cm depth; T_6 – Tillage upto 20 cm depth and T_7 – Tillage upto 40 cm depth

Table 4.23: Depth-wise root length density (m m^{-3}) under different tillage treatments at 120 and 150 DAS for the second wheat crop season (2003-04)

Treatments*	120 DAS			150 DAS		
	Depth (m)					
	0.0-0.1	**0.1-0.2**	**0.2-0.3**	**0.0-0.1**	**0.1-0.2**	**0.2-0.3**
T_1	0.792	0.218	0.056	1.105	0.302	0.068
T_2	1.188	0.271	0.068	1.475	0.373	0.097
T_3	1.314	0.320	0.123	1.963	0.464	0.165
T_4	1.839	0.442	0.161	2.486	0.582	0.206
T_5	0.872	0.230	0.061	1.149	0.327	0.072
T_6	0.956	0.253	0.074	1.320	0.368	0.098
T_7	1.210	0.294	0.110	1.860	0.438	0.154
LSD (0.05)	**0.118**	**0.029**	**0.015**	**0.125**	**0.032**	**0.016**

*T_1 – No tillage; T_2 – Tillage upto 10 cm depth; T_3 – Tillage upto 20 cm depth; T_4 – Tillage upto 40 cm depth; T_5 – No tillage; T_6 – No tillage and T_7 – No tillage

4.4.3.3 Root volume density (RVD)

The depth-wise RVD values under different tillage treatments were determined at 120 and 150 DAS in two wheat seasons (2002-03 and 2003-04) and are presented in Table 4.24 and 4.25, respectively. A perusal of data in Table 4.24 indicated that during 2002-03, RVD values at 120 and 150 DAS were statistically at par in treatments T_4 and T_7, but were significantly higher as compared to T_1, T_2, T_3, T_5 and T_6, respectively in all the soil depths (0.0-0.1, 0.1-0.2 and 0.2-0.3 m).

Table 4.24: Depth-wise root volume density (x 10^2 m^3 m^{-3}) under different tillage treatments at 120 and 150 DAS for the first wheat crop season (2002-03)

Treatments*	120 DAS			150 DAS		
	Depth (m)					
	0.0-0.1	0.1-0.2	0.2-0.3	0.0-0.1	0.1-0.2	0.2-0.3
T_1	0.760	0.206	0.029	0.827	0.247	0.048
T_2	0.870	0.238	0.036	0.940	0.290	0.067
T_3	1.013	0.284	0.054	1.130	0.350	0.097
T_4	1.150	0.340	0.082	1.383	0.433	0.144
T_5	0.890	0.244	0.038	0.960	0.303	0.063
T_6	1.030	0.296	0.056	1.150	0.367	0.093
T_7	1.160	0.354	0.087	1.400	0.453	0.139
LSD (0.05)	**0.021**	**0.027**	**0.006**	**0.022**	**0.030**	**0.018**

***T_1 – No tillage; T_2 – Tillage upto 10 cm depth; T_3 – Tillage upto 20 cm depth; T_4 – Tillage upto 40 cm depth; T_5 – Tillage upto 10 cm depth; T_6 – Tillage upto 20 cm depth and T_7 – Tillage upto 40 cm depth**

The RVD values on 120 DAS during second year (2003-04) of the study were significantly higher in T_4 as compared to T_1, T_2, T_3, T_5, T_6 and T_7 in all the three consecutive soil depths (0.0-0.1, 0.1-0.2 and 0.2-0.3 m). The next higher was T_7 (at par with T_3) which had significantly higher RVD values as compared to T_1, T_2, T_5 and T_6 (Table 4.25). Similar trend was observed in RVD value on 150 DAS.

Table 4.25: Depth-wise root volume density (x 10^2 m^3 m^{-3}) under different tillage treatments at 120 and 150 DAS for the second wheat crop season (2003-04)

Treatments*	120 DAS			150 DAS		
	Depth (m)					
	0.0-0.1	0.1-0.2	0.2-0.3	0.0-0.1	0.1-0.2	0.2-0.3
T_1	0.763	0.215	0.030	0.870	0.266	0.050
T_2	0.887	0.254	0.038	0.977	0.314	0.075
T_3	1.067	0.304	0.062	1.156	0.375	0.104
T_4	1.160	0.363	0.094	1.417	0.460	0.160
T_5	0.790	0.221	0.033	0.930	0.278	0.056
T_6	0.823	0.241	0.041	0.973	0.303	0.068
T_7	1.043	0.293	0.058	1.130	0.357	0.097
LSD (0.05)	**0.027**	**0.020**	**0.005**	**0.029**	**0.031**	**0.008**

***T_1 – No tillage; T_2 – Tillage upto 10 cm depth; T_3 – Tillage upto 20 cm depth; T_4 – Tillage upto 40 cm depth; T_5 – No tillage; T_6 – No tillage and T_7 – No tillage**

4.4.3.4 Root porosity (RP)

An observation of data on RP of wheat as influenced by different treatments revealed that during both the years of the study (2002-03 and 2003-04), tillage at different depths had significant influence on the root porosity at 90, 120 and 150 DAS (Table 4.26 and 4.27). The per cent RP values during the first year of the study were significantly lower at 90, 120 and 150 DAS in T_4 (at par with T_7) than T_1, T_2, T_3, T_5 and T_6 (Table 4.26), respectively.

During the second year of the study (2003-04), the per cent RP values at 90, 120 and 150 DAS were significantly lower in treatment T_4 as compared to all other treatments (Table 4.27). The next lower was T_7 which was statistically at par with treatment T_3, but significantly different from T_1, T_2, T_5 and T_6. In both the years of study the treatments T_4 and T_7 showed lower per cent RP values as compared to all the other treatments. The highest per cent RP value was, however, observed in T_1 in both the years of study.

Table 4.26: Root porosity (%) under different tillage treatments at 0.0-0.1 m soil depth for the first wheat crop season (2002-03)

Treatments*	90 DAS	120 DAS	150 DAS
T_1	35.13	24.77	19.60
T_2	29.20	19.50	15.27
T_3	24.57	13.57	11.60
T_4	17.97	8.77	5.76
T_5	29.67	19.90	15.73
T_6	24.47	13.67	11.67
T_7	17.63	8.63	6.10
LSD (0.05)	**0.83**	**0.96**	**0.83**

*T_1 – No tillage; T_2 – Tillage upto 10 cm depth; T_3 – Tillage upto 20 cm depth; T_4 – Tillage upto 40 cm depth; T_5 – Tillage upto 10 cm depth; T_6 – Tillage upto 20 cm depth and T_7 – Tillage upto 40 cm depth

Table 4.27: Root porosity (%) under different tillage treatments at 0.0-0.1 m soil depth for the second wheat crop season (2002-03)

Treatments*	90 DAS	120 DAS	150 DAS
T_1	33.97	24.27	19.33
T_2	29.10	18.67	14.87
T_3	23.30	12.67	10.90
T_4	17.37	7.97	5.40
T_5	32.90	21.57	17.63
T_6	27.10	17.50	13.20
T_7	24.60	13.50	11.67
LSD (0.05)	**1.54**	**1.12**	**1.03**

*T_1 – No tillage; T_2 – Tillage upto 10 cm depth; T_3 – Tillage upto 20 cm depth; T_4 – Tillage upto 40 cm depth; T_5 – No tillage; T_6 – No tillage and T_7 – No tillage

4.4.2.5 Rooting depth (RD)

The data pertaining to rooting depth have been presented in Table 4.28 and 4.29 for the year 2002-03 and 2003-04, respectively. A study of data in Table 4.28 observed that during first year of the study, RD values at 30, 60, 90, 120 and 150 DAS were significantly higher in treatment T_4 (at par with T_7) as compared to T_1, T_2, T_3, T_5 and T_6. Additionally, T_3 and T_6 (which were at par among themselves) had significantly higher RD values as compared to T_1, T_2, and T_5, respectively.

Table 4.28: Rooting depth (cm) under different tillage treatments for the first wheat crop season (2002-03)

Treatments*	30 DAS	60 DAS	90 DAS	120 DAS	150 DAS
T_1	4.6	9.7	19.2	22.6	24.8
T_2	5.0	10.9	21.0	24.8	26.6
T_3	5.1	13.6	22.8	26.9	29.1
T_4	5.5	16.1	25.3	30.6	34.0
T_5	5.0	10.7	20.6	25.0	25.5
T_6	5.2	13.4	22.5	26.9	28.5
T_7	5.6	16.2	25.0	31.0	32.8
LSD (0.05)	**0.2**	**0.5**	**1.1**	**1.6**	**1.4**

***T_1 – No tillage; T_2 – Tillage upto 10 cm depth; T_3 – Tillage upto 20 cm depth; T_4 – Tillage upto 40 cm depth; T_5 – Tillage upto 10 cm depth; T_6 – Tillage upto 20 cm depth and T_7 – Tillage upto 40 cm depth**

During the second year of the study (2003-04), the RD values at 90, 120 and 150 DAS were significantly higher in treatment T_4 as compared to all other treatments (Table 4.29). The next higher RD values was under T_7 which was statistically at par with treatment T_3, but significantly different from T_1, T_2, T_5 and T_6, respectively. In both the years of study the treatments T_4 and T_7

showed higher RD values as compared to all the other treatments. The lowest RD value was, however, observed in T_1 in both the years of study.

Table 4.29: Rooting depth (cm) under different tillage treatments for the second wheat crop season (2003-04)

Treatments*	30 DAS	60 DAS	90 DAS	120 DAS	150 DAS
T_1	4.7	10.4	21.1	22.9	25.3
T_2	5.0	11.5	22.6	25.1	27.2
T_3	5.3	14.1	24.3	27.2	29.7
T_4	5.7	18.0	26.0	31.0	35.1
T_5	4.7	10.6	21.7	23.1	25.4
T_6	4.8	10.9	22.4	24.2	26.1
T_7	5.1	13.4	23.5	25.8	28.3
LSD (0.05)	**0.2**	**0.9**	**1.0**	**1.4**	**1.6**

***T_1 – No tillage; T_2 – Tillage upto 10 cm depth; T_3 – Tillage upto 20 cm depth; T_4 – Tillage upto 40 cm depth; T_5 – No tillage; T_6 – No tillage and T_7 – No tillage**

4.4.4 Crop yield

The data pertaining to grain, straw and biological yield have been presented in Table 4.30 and 4.31 for the year 2002-03 and 2003-04, respectively. A study of data in Table 4.30 observed that during first year of the study, grain, straw and biological yields were significantly higher in treatment T_4 (at par with T_7) as compared to T_1, T_2, T_3, T_5 and T_6, respectively. Additionally, T_3 and T_6 (which were at par among themselves) had significantly higher grain, straw and biological yield as compared to T_1, T_2, and T_5, respectively.

Table 4.30: Crop yield under different tillage treatments for the first wheat crop season (2002-03)

Treatments*	Grain yield (Mg ha^{-1})	Straw yield (Mg ha^{-1})	Biological yield (Mg ha^{-1})
T_1	2.10	3.42	5.52
T_2	2.39	3.80	6.19
T_3	2.86	4.57	7.41
T_4	3.35	5.78	9.13
T_5	2.36	3.73	6.09
T_6	2.90	4.50	7.23
T_7	3.39	5.53	8.92
LSD (0.05)	**0.18**	**0.15**	**0.19**

***T_1 – No tillage; T_2 – Tillage upto 10 cm depth; T_3 – Tillage upto 20 cm depth; T_4 – Tillage upto 40 cm depth; T_5 – Tillage upto 10 cm depth; T_6 – Tillage upto 20 cm depth and T_7 – Tillage upto 40 cm depth**

It is evident from Table 4.31 that grain, straw and biological yields during second wheat crop season (2003-04) were also significantly higher in treatment T_4 as compared to T_1, T_2, T_3, T_5, T_6 and T_7, whereas, T_7 had significantly higher grain, straw and biological yield as compared to T_1, T_2, T_5 and T_6, but remained statistically at par with treatment T_3. The next higher was T_3 which was significantly different in grain, straw and biological yield from T_1, T_2, T_5 and T_6. The lowest crop yield (grain, straw and biological yield) was, however, observed in T_1 and highest in T_4 treatment in both the years of study.

Table 4.31: Crop yield under different tillage treatments for the second wheat crop season (2003-04)

Treatments*	Grain yield ($Mg\ ha^{-1}$)	Straw yield ($Mg\ ha^{-1}$)	Biological yield ($Mg\ ha^{-1}$)
T_1	2.16	3.52	5.68
T_2	2.66	4.11	6.77
T_3	3.00	5.07	8.01
T_4	3.53	6.25	9.78
T_5	2.55	3.78	6.33
T_6	2.76	4.12	6.88
T_7	2.99	5.24	8.23
LSD (0.05)	**0.15**	**0.19**	**0.23**

***T_1 – No tillage; T_2 – Tillage upto 10 cm depth; T_3 – Tillage upto 20 cm depth; T_4 – Tillage upto 40 cm depth; T_5 – No tillage; T_6 – No tillage and T_7 – No tillage**

DISCUSSION

CHAPTER-V

DISCUSSION

The experimental results obtained from the present investigation entitled, "Soil-water dynamics, root growth and wheat yield in a sequentially deep tilled post-rice soil" have been described in detail in previous chapter. In this chapter attempt have been made to highlight the important findings and to interpret the different tillage treatment effects on various parameters studied by establishing suitable 'cause' and 'effect' relationship in the light of available evidence and literature under the following heads: -

5.1 Initial soil properties

5.2 Soil studies

5.3 Plant growth parameters

5.4 Root studies

5.5 Crop yield

5.1 Initial soil properties

The experimental site was terraced in year 1975 for the purpose of crop production. Prior to this, the area was under tea plantation (Bhagat, 1982). After terracing, the crops of maize and wheat were grown in a sequence for 23 years. After the year 1998, the rice-wheat system replaced maize-wheat sequence. The soils of the experimental site were fairly stabilized after these were cut, filled and graded at several places while terracing. The mechanical analysis of the study area revealed that the texture of the upper layer (0.00-

0.15 m) was silty clay loam (Table 4.1). The lower layers (0.15-0.30 and 0.30-0.45 m), however, showed increase in clay content. The soils of the study area are fairly permeable to water with a basic intake rate of 0.92 cm hr^{-1}. The water retention in the surface layer (0.00-0.15 m) is poor in comparison to the lower layers. The "available water capacity (AWC)" of the soil defined as per the classical concepts, "water retained in the range of field capacity (10 to 33.3 kPa suction) to wilting point (1500 kPa suction)" is quite low. For the surface 0.00-0.15 m, it was 12.1 per cent while lower 0.15-0.30 and 0.30-0.45 m depths showed AWC to be 14.1 per cent and 16.8 per cent by volume, respectively. It was observed that at all the depths, the decrease in water content from 0 to 10 kPa suction was quite rapid and then gradual beyond this suction. This decrease for the surface depths was observed to be as high as 22 per cent by volume. This indicated that most of the water after rainfall event or irrigation application drains down the profile and less amount is available for the plant growth.

5.2 Soil studies

The crops were grown in rice-wheat sequence and wheat was the test crop. Soil studies were performed at sowing and after the harvest of rice and wheat crops. Soil studies at the time of sowing of wheat crop showed that no-tilled treatment (T_1) had the highest bulk density (ρ_b) values. Puddling in rice destroys soil structure and converted the soil aggregates and peds into soft plastic mud and thereby practically eliminating the water transmission macro-pores (Sharma and De Datta, 1986; Acharya and Sood, 1992). Puddled soils shrink on drying, became compact and hard (Bolton and De Datta, 1979; Sur *et al.*, 1981; Bhagat and Acharya, 1987; Prihar *et al.*, 1990). No-tilled treatment in the present study in both the years, therefore, showed the highest 'ρ_b' values compared to all other treatments (Pelegrin *et al.*, 1990; Khakural *et al.*, 1992).

Successive increases in the depth of tillage showed decrease in 'ρ_b' values to the depths upto which the tillage operation was done. Lowest 'ρ_b' values were observed in T_4 treatment where deep tillage was done upto a depth of 40 cm. Such observations were recorded in both the years of the study and both at sowing and harvest of wheat crop (Figure 4.5, 4.6, 4.7 and 4.8). This may be due to the increase in non-capillary porosity and reduction in mass per unit volume. Since, total porosity (f) and 'ρ_b' are inversely related to each other, hence even depth-wise, the layer that had the higher 'f', showed the lower bulk density and vice-versa. Similar trends in low 'ρ_b' values have been observed by various other workers (Sharma *et al.*, 1971; Mielke *et al.*, 1986; Gupta 1987; Campbell and Akhtar, 1989; Aggarwal *et al.*, 1992; Bhagat and Chand, 1994; Mehta *et al.*, 1996; Gajri *et al.*, 1997; Akinci, 2004).

During the second year of the crop study, the residual effect of the deep tillage was quite discernable in treatment T_7 where deep tillage-no tillage sequence was followed with a puddled rice crop in between. The 'ρ_b' values in T_7 were less than T_1, T_2, T_5 and T_6, which also clearly indicated the positive effect of deep tillage even after inclusion of a puddled lowland crop. The effect of deep tillage in second year was reflected more in lower layers in T_7. Since the puddling effect are mostly confined in the upper layers and the lower layers are left as such which may be the reason of more pronounced effect of deep tillage in lower layers (Zhao *et al.*, 1997).

The soil penetration resistance (SPR) values decreased with tillage and moisture content in both the years of the study. T_4 treatment in the first year and T_7 in the second year of the study had lower values of SPR compared to other treatments (Figure 4.9, 4.10, 4.11, 4.12, 4.13 and 4.14). Since these two treatments had the lower 'ρ_b' values, hence this may be the reason of lower SPR in the treatments (Kumar *et al.*, 1971; Kisu, 1978). Increase in the 'ρ_b' increases the resistance to penetration in soil. Any treatment, which increases ρ_b will increase SPR values. In the present study, these observations were made in T_1 (no tillage treatment). As these successive tillage treatments were imposed (T_2, T_3, T_5 and T_6), SPR values progressively decreased. This reduction is similar to that observed in 'ρ_b' values. The reduction in SPR values due to ρ_b was also reported by earlier workers (Pelegrin *et al.*, 1990; Bhagat and Verma, 1991; Pikul, 1999; Busscher, 2000; Ishaq *et al.*, 2002; Abu Hamdeh, 2003). The tillage operations have further been reported to break, pulverize and loosen the soil mass and thus reduces the SPR values (Gupta and Jaggi, 1979).

In general, the volumetric water content (θ) values under no-tilled treatment (T_1) were higher at all the depths compared to all the other treatments. This increase in 'θ' values may be a consequence of the higher 'ρ_b' in no-tilled treatment (Figure 4.15, 4.16, 4.17 and 4.18). Such observations are also supported by Carefoot (1990), Bhagat and Chand (1994) and Lawerence *et al.* (1994). It was, however, noted that immediately after the application of irrigation or a rainfall event, the 'θ' values were higher under tilled treatments and maximum values were observed under deep tillage (T_4) (Carlson, 1978; Unger, 1979; Bhagat and Acharya, 1987; Sharma and Acharya, 1993). The loss of water was more under T_4 probably because of rapid drainage due to the presence of macro-pores. This would also indicate that the water retention at prolonged periods was less in deep tillage compared to no-tilled treatment (Figure 4.19, 4.20, 4.21, 4.22, 4.23, 4.24, 4.25, 4.26, 4.27, 4.28, 4.29, 4.30, 4.31 and 4.32). The adverse effects of this water loss were, however, not noticed on crop growth because of recommended irrigation and adequate rainfall in both the years of the study. Such observations have also been reported by Bhagat and Acharaya (1989).

The tillage operations significantly increased the saturated hydraulic conductivity (k_s) values as compared to no-till plots in both the years of study (Figure 4.33, 4.34, 4.35 and 4.36). The increase in 'k_s' values in tilled plots could be attributed to loosening of the soil by tillage operations (Unger and Cassel, 1991; Aggarwal *et al.*, 1992, Aggarwal *et al.*, 1997; Bordovsky, 1999). The 'k_s' values decreased with depth also. The increase in fineness of the texture with depth may be responsible for this decrease in 'k_s' values. Further, low ks values in lower layers may also be attributed to the higher 'ρ_b' and mechanical impedance (Chang, 1992). Such observations were recorded at both years during sowing and harvesting of wheat crop.

The *in situ* hydraulic conductivity [K(θ)] values determined during the internal drainage process of a pre-saturated soil profile at the experimental area showed the lower K(θ) values for the surface 0.0-0.1 and 0.1-0.2 m depths, whereas, the lower depths had higher K(θ) values (Figure 4.37). The values of the exponent for 'θ', which is related to the permeability function, were the lowest for the depth (0.0-0.1 m) in comparison to the other depths. There were differences in the field and laboratory determined hydraulic values. The 'k_s' values were generally greater for the field data than the laboratory data. These differences have to be seeked in the assumptions outlined in the two methods. In the laboratory, a comparatively smaller sample is used which may not exactly represent the field conditions. In the internal drainage field method, on the other hand, the data are based on the measurement of greater area and hence K(θ) values could be more representative to the field situations to correlate the fluxes within the root zone. A similar usage of the field data have been suggested by La Rue *et al.* (1968), Van Bavel *et al.* (1968), Bhagat and Acharya (1988) and Bhagat *et al.* (1999). Hence, hydraulic conductivity values obtained from the field data have been used to measure the fluxes within the root zone in these studies. The K(θ) values were determined within the experimental site during both the years. The data had a very close agreement for both the years. No further attempt was however made to quantify the spatial variability of the field determined hydraulic conductivity within the experimental site, which was assumed to be uniform.

In order to estimate the soil water dynamics in the profile, the data on matric potential (Ψ_m) and 'θ' values were taken for the entire wheat growth period. The total rainfall received during the crop growth period 2002-03 and 2003-04 were 209.5 and 417.3 cm, respectively. The distribution of rain along with changes in 'Ψ_m' are shown in Figure 4.38, 4.39, 4.40, 4.41, 4.43, 4.42 and 4.44 (2002-03) and Figure 4.45, 4.46, 4.47, 4.48, 4.49, 4.50 and 4.51 (2003-04). After rain or irrigation as the dry period progressed, the 'Ψ_m' values were decreased in all the treatments (Figure 4.38, 4.39, 4.40, 4.41, 4.43, 4.42, 4.44, 4.45, 4.46, 4.47, 4.48, 4.49, 4.50 and 4.51). The decrease was comparatively greater in the surface (0.0-0.1 and 0.1-0.2 m) compared to sub-surface depths (0.2-0.3, 0.3-0.4 and 0.4- 0.5 m). The decrease in 'Ψ_m' values was primarily as a result of the water uptake by the roots and evaporation at the soil surface. However, the profile was frequently rewetteu by either winter rain or applied irrigation. Surface depth seems to have contributed maximum water loss. No-tilled plots (T_1) had dried up quickly at the surface and decreased in 'Ψ_m' values was noticed. Surface layers in T_1 had lower 'Ψ_m' values compare to sub-surface layers. During rainless period, the higher 'Ψ_m' values in T_1 (no tillage) at lower depths may be a consequence of higher water retention in these treatments (Bhagat and Chand, 1994). In T_4 (deep tillage), due to the secondary planes of evaporation coupled with fast drainage may be a reason for low 'Ψ_m' values in this treatment.

When the hydraulic potential (the sum of matric and gravitational potentials) became lower than that of the layer immediately below it, an upward movement of water towards this layer was induced. This is evident from changes in hydraulic gradients (Figure 4.52, 4.53, 4.54, 4.55, 4.56, 4.57, 4.58, 4.59, 4.60, 4.61, 4.62, 4.63, 4.64 and 4.65), the soil water content (Figure 4.15, 4.16, 4.17, 4.18, 4.19, 4.20, 4.21, 4.22, 4.23, 4.24, 4.25, 4.26, 4.27, 4.28, 4.29, 4.30 and 4.31), the hydraulic flux values (Figure 4.66, 4.67, 4.68, 4.69, 4.70, 4.71, 4.72, 4.73, 4.74, 4.75, 4.76, 4.77, 4.78 and 4.79) at different depths of soil profile under different treatments. The hydraulic gradient below 0.4 m depth in all the treatments remained around the line of zero flux for most of the growth period. However, changes in hydraulic gradient were noticed after 130 days of crop growth. Past studies have defined the effective rooting depth as the maximum depth at which the hydraulic gradient was zero (Mc Gowan, 1974). In these studies, the maximum rooting depth worked out to be 30-37 cm for the entire crop period. This is substantiated by the data on the changes in the magnitude and direction of the hydraulic flux within the profile depths under different treatments. The direction of hydraulic flux indicated that the crop extracted water mainly upto the 0.3-0.4 m layer during most of the crop period in all the treatments. At certain, periods i.e. around 60, 100 and 125 days, the surface layers were quite wet and met the evapotranspiration demand besides some downward movement. While at other periods, the flux was mostly upward. The three periods i.e. around 60, 100 and 125 days received rainfall or irrigation, while at other periods; the relative effective depth for the water withdrawal was reflected from the soil profile under different treatments. Similar results were also obtained by Gregory *et al.* (1978) and Bhagat and Acharya (1988). Such estimates serve to indicate the maximum identifiable depth of water extraction but do not guarantee the presence or activity of roots. Roots may be present in a particular layer without extracting water from the layer or water may move upward through the soil before being taken up by the crops. Thus, the estimates based on the changes in the energy status of water must be correlated with the actual rooting density determination (Bhagat and Acharya, 1988).

The steady-state infiltration rate determined at harvest of crop during both years was higher in deep-tilled plots as compared to other treatments which might be due to increase in macro-porosity by loosening of soil to a greater depths (Figure 4.80, 4.81, 4.82, 4.83, 4.84, 4.85, 4.86, 4.87, 4.88, 4.89, 4.90, 4.91, 4.92 and 4.93). Aggarwal *et al.* (1992) have also reported that steady-state infiltration rate was significantly higher under deep tillage than minimum tillage system in silty loam soil of wheat crop in Doon Valley. Studies conducted at other places have also reported higher steady-state infiltration rate under deep tillage than other treatments (Aggarwal *et al.*, 1997; Abu Hamdeh, 2003; Barzegar, 2004). The no-tilled plots registered lowest basic intake rate, however, these values increased as the depth of tillage increased which indicated that as the profile was loosened to different depths, the basic intake rate increased. The values became highest for T_4 (40 cm deep tillage). Such results have also been reported by Bhagat (1987).

The different tillage treatments imposed in this study not only altered the soil water regime at different profile depths but also affected the thermal regime (Figure 4.67, 4.68, 4.69, 4.70, 4.71, 4.72, 4.73 and 4.74). Alteration of soil temperature even by 1^0C has been known to significantly affect the crop growth (Barley, 1970). The weekly soil temperature in both wheat crop seasons during 2002-03 and 2003-04 indicated that deep/conventional tillage had higher minimum temperature at 0630 hours and lower maximum temperature at 1430 hours compared to no tillage in 0.05 m soil depth. Similarly, in 0.1 m soil depth, the deep tillage had higher minimum temperature at 0630 hours and lower maximum temperature at 1430 hours compared to no tillage. This would indicate that deep tillage to some extent moderated the temperature favourably and also resulted in a better stand of crop. The treatment of no tillage (T_1) lowered the soil temperature and did not moderate it in any way. It is likely the rapid loss of water at the soil surface under this treatment resulted in earlier desiccation of the surface layer and thereby decreased the heat capacity of soil to some extend. Such results have also been reported by Bhagat and Acharya (1988).

5.3 Plant growth parameters

The plant growth parameters of wheat recorded were emergence count (Table 4.5 and 4.6), seedling emergence parameters (Table 4.7 and 4.8), plant height (Table 4.9 and 4.10), number of tillers (Table 4.11 and 4.12) and dry matter accumulation (Table 4.12 and 4.13). These were significantly influenced by different tillage treatments. In both the years of study, the emergence count per m^2 during both the years of experimentation was significantly higher in deep (T_4)/ conventional tillage (T_2 and T_3) as compared to no tillage (T_1) which can be attributed to loosening of soil which increased the soil temperature may be due to increased heat absorbance from the sun and hence enhanced early emergence and emergence count in winter sown wheat crop (Drury *et al.*, 1999). Enhanced radiation interception due to profuse tillering as well as better nutrition of crop plants by tillage treatments might have increased the photosynthetic rate which was reflected in significant increase in dry matter accumulation at all the dates of observation. Significantly lowest emergence count was, however, observed in no tillage treatment which may be due to the reason that soils after rice harvest become hard for penetration, because of their massive structure, high bulk density and increased mechanical impedance. Such results are also supported by Brar *et al.* (2000) and Sharma and Bhagat (1993).

The seedling emergence parameters *viz.* initiation of emergence (days), days for attaining constant emergence and emergence velocity (per cent per day) were significantly affected by different tillage treatments recorded during both the crop seasons. In 2002, 90 per cent and 84 per cent of the plants emerged after 8.3 and 9.3 days with the deep and conventional tillage treatments, respectively, whereas, 12.7 days were required under no tillage to attain emergence of 70.7 per cent. The deep tillage treatment had a significantly higher emergence rate than all the other treatment. In this study, the no tillage treatment had delayed emergence due to the cooler wetter soil initially during seedling emergence period and poor seedbed conditions. Other studies have also indicated delayed emergence primarily as a result of decreased soil temperature (Al-Darby and Lowery, 1987; Gupta *et al.*, 1988; Fortin and Pierce, 1990; Fortin and Pierce, 1991).

The plant height in wheat crop during both the years continued to increase with age upto 150 DAS, thereafter there was no further increase as the crop proceeded towards maturity. In general, plant height recorded after 30, 60, 90, 120 and 150 DAS of wheat during 2002-03 and 2003-04 was significantly higher in plots where deep tillage (T_4) treatment was imposed which was followed by conventional tillage (T_2 and T_3). However, significantly lowest plant height was recorded in no tillage (T_1) in both the years of the study. Smaller plant height and lesser number of tillers per m^2 of wheat under no tillage treatment after transplanting were probably associated with poor physical conditions after the puddled wetland rice. The higher ρ_b of soil and penetration resistance increased the soil compaction and soil strength resulting in smaller plant height (Peterson *et al.*, 1984; Dass and Kashyapi, 1992; Padma Raju and Dev, 1996).

A progressive increase in tiller count per m^2 of wheat was observed upto 90 DAS in all the tillage treatments and thereafter there was no increase in tillers upto maturity. In both the wheat crop seasons, the number of tillers was significantly higher in deep (T_4) / conventional (T_2 and T_3) tillage than no tillage (T_1) in 30, 60 and 90 DAS. The lesser number of wheat tillers per unit area after puddled wetland rice were associated with the poor physical conditions leading to poor growth of succeeding wheat crop in no tillage. Such results are also supported by Das and Mukherjee (1995) and Sandeep *et al.* (2004) findings.

The dry matter accumulation during both the wheat crop seasons (2002-03 and 2003-04) was significantly higher in deep (T_4) / conventional (T_2 and T_3) tillage than no tillage (T_1) at all the dates of observations. The higher dry matter production could be attributed to favourable effect of soil physical environment created by deep tillage which helped in controlling weeds, free exchange of gases in soil and air that enhanced root growth for greater uptake of water, higher plant population and better use of nutrients and produced more number of effective tillers in wheat. Higher dry matter accumulation under deep tillage treatments was also reported by Gajri (1997), Ferreras (2000) and Gangwar *et al.* (2004).

5.4 Root studies

The role of tillage is to make rootable spaces within the soil by reducing the soil strength and increasing the macro-porosity. Loosening of root- restricting hard soil layers by tillage promotes root growth into deeper soil layers. Moreover, tillage helps in controlling weeds, improvement in soil physical properties, free exchange of gases in soil and air which results in better root growth, their penetration to sub-surface depth and hence greater utilization of sub-soil moisture (Orellana *et al.*, 1990; Acharya and Bhagat, 1984; Bhagat and Acharya, 1987; Ishaq *et al.*, 2003; Xi Ying *et al.*, 2004). The root mass density (RMD), root length density (RLD), root volume density (RVD) and rooting depth (RD) values were higher in deep tillage (T_4) treatment which was followed by conventional tillage (T_2 and T_3), however, significantly lower value was recorded in no tillage (T_1) at 30, 60, 90, 120 and 150 DAS in both the years of the study (Table 4.14, 4.15, 4.18, 4.19, 4.24, 4.25, 4.26 and 4.27). The higher values of root parameters under deep-tilled plots (T_4) were mainly as a result of loosening of sub-surface compact layers. The shattering of the compact layers not only helped in the better elongation and proliferation of roots, but also decreased the impedance to water movement and providing thereby a better environment for the plant growth. Similar observations have also been made by other workers (Trouse, 1979; Acharya and Bhagat, 1984; Bhagat and Acharya, 1987; Gajri *et al.*, 1991; Sharma and Acharya, 1993; Thompson, 2001; Ishaq *et al.*, 2003; Xi Ying *et al.*, 2004). The lower RMD, RLD, RVD and LLR values in no tillage (T_1) could be attributed to the increased soil strength at the surface as a result of soil compaction. The increase in bulk density in the surface layers as a result of compaction provided a hydraulic barrier at the surface resulting in water standing after rain for comparatively more time. This might have adversely affected air-water relations resulting in poor root growth (Ferreras, 2000). The RMD, RLD and RVD values for the depths 0.0-0.1, 0.1-0.2 and 0.2-0.3 m were also higher in deep tillage treatment which were followed by conventional tillage, however, significantly lower values were recorded in no tillage at 90, 120 and 150 DAS in both the years of the study (Table 4.16, 4.17, 4.20, 4.21, 4.24 and 4.25). In case of wheat, root porosity under T_4 at three periods (90, 120 and 150 DAS) was significantly lower as compared to conventional and no tillage treatments, which resulted in higher RMD and RLD values (Table 4.22 and 4.23). Such results have been obtained by Jensen *et al.* (1969).

5.5 Crop yield

The tillage system has a positive effect on growth and yields of crops because it alleviates soil constraints which limit the yield. The crop performance under different tillage systems depend upon the site-specific soil and climate constraints and allied management practices (irrigation, fertilizer management, weed control and residue status). The crop yields of wheat were significantly influenced by different tillage treatments in both wheat crop seasons (Plate 2, 3, 4 and 5) during 2002-03 and 2003-04 (Table 4.28 and 4.29). The grain, straw and biological yields were significantly higher in plots where deep tillage (T_4) treatment was adopted which were followed by conventional tillage (T_2 and T_3). This could be associated with improvement in soil physical properties (bulk density, total porosity, mechanical impedance, saturated hydraulic conductivity, infiltration etc.), which helped in controlling weeds and free exchange of gases in soil and air which results in better root growth. Moreover, the deep tillage practices also encourage deeper rooting and hence better mining of water by the wheat crop resulting in high yields (Sharma and Acharya, 1993; Bhagat and Chand, 1994; Gajri *et al.*, 1997; Bajpai and Tripathi, 2000; Busscher and Baurer, 2003; Abu Hamdeh, 2003; Tomar, 2003; Ishaq, 2003; Murty, 2004). However, significantly lower grain, straw and biological yields were recorded in no tillage during both the years of the study. The lower wheat yield in no tillage (T_1) plots was associated with heavy crop-

Plate 2: Wheat crop at 142 DAS under treatment T_1 (no tillage)

Plate 3: Wheat crop at 142 DAS under treatment T_4 (tillage upto 40 cm depth)

Plate 4: Wheat crop at harvesting under treatment T_1 (no tillage)

Plate 5: Wheat crop at harvesting under treatment T_4 (tillage upto 40 cm depth)

weed competition. The population of weeds was significantly higher in no tillage than in deep/conventional tillage plots (Sharma and Kharwara, 1994; Singh *et al.*, 1998).

SUMMARY

CHAPTER-VI

SUMMARY

Field experiments were conducted on the project entitled, "Soil-water dynamics, root growth and wheat yield in a sequentially deep tilled post-rice soil" at the Experimental Farm of the Department of Soil Science, CSK Himachal Pradesh Krishi Vishvavidyalaya, Palampur (Kangra) for two years (2002-03 and 2003-04) in rice-wheat cropping sequence under irrigated conditions with the following broad objectives: -

1. To study the effect of depth of tillage on root growth of wheat in post-rice soil.
2. To study the effect of depth of tillage on soil and plant-water relations.
3. To study the effect of depth and frequency of tillage on root growth pattern of wheat *vis-a-vis* wheat yield.

The experimental site was situated about 1290 m above mean sea level in north-west Himalayas and had sub-temperate humid climate. The mechanical analysis of the profile revealed that the texture of the upper layer (0.00-0.15 m) was silty clay loam. The lower layers (0.15-0.30 and 0.30-0.45 m), however, showed increase in clay content. The soil of the study area was acidic in reaction, categorized as medium in organic carbon, medium to low in available nitrogen, phosphorous and potassium and classified as Alfisols, Typic Hapluadalf. The available water capacity (AWC) of the soil was 12.1 per cent for the surface (0.00-0.15 m), while lower 0.15-0.30 and 0.30-0.45 m depths showed AWC to be 14.1 per cent and 16.8 per cent by volume, respectively. It was observed that at all the depths, the decrease in water content from 0 to 10 kPa suction was quite rapid and then gradual beyond this suction.

Successive increases in the depth of tillage showed decrease in bulk density (ρ_b) values to the depths upto which the tillage operation was done. Lowest ρ_b values were observed in T_4 treatment where deep tillage was done upto a depth of 40 cm. Such observations were recorded in both the years of the study and both at sowing and harvest of wheat crop. During the second year of the crop study, the residual effect of the deep tillage was quite discernable in treatment T_7 where deep tillage-no tillage sequence was followed with a puddled lowland rice crop in between. The ρ_b values in T_7 were less than T_1, T_2, T_5 and T_6, which also clearly indicated the positive effect of deep tillage even after inclusion of a puddled crop.

The soil penetration resistance (SPR) values decreased with tillage and moisture content in both the years of the study. T_4 treatment in the first year and T_7 in the second year of the study had lower values of SPR compared to other treatments. Lower ρ_b values contributed towards low values of SPR.

The volumetric water content (θ) values under no-tilled treatment (T_1) were higher at all the depths compared to other treatments. It was, however, noted that immediately after the application of irrigation or a rainfall event, the θ values were higher under tilled treatments and maximum values were observed under deep tillage (T_4).

The saturated hydraulic conductivity values decreased with depth from 0.00-0.075 m to 0.075-0.15 and 0.15-0.30 m. The unsaturated hydraulic conductivity [K(θ)] values determined *in situ*, showed lower values for the surface 0.0-0.1 and 0.1-0.2 m depth, whereas, the deeper depths had higher K(θ) values. Moreover, the hydraulic conductivity values obtained from the field data were greater than those obtained from the laboratory data.

The changes in matric potential (Ψ_m) values observed at different profile depths during the period of crop growth under different treatments showed that for most of the time the water needs of the crop were met by the layers upto 0.3 m depth. Upper layers in no-tilled plots (T_1) dried up quickly and decrease in 'Ψ_m' values was noticed. In deep tillage, the changes in 'Ψ_m' values were observed to the greater depths.

The hydraulic gradient below 0.4 m depth in all the treatments remained around the line of zero flux for most of the growth period. However, changes in hydraulic gradient were noticed after 130 days of crop growth. This was further substantiated by the data on the changes in the magnitude and direction of the hydraulic flux within the profile depths under different treatments. The direction of hydraulic flux indicated that the crop extracted water mainly upto the 0.3-0.4 m layer during most of the crop period in all the treatments. At certain, periods i.e. around 60, 100 and 125 days, the surface layers were quite wet and met the evapotranspiration demand besides some downward movement. While at other periods, the flux was mostly upward.

The *infiltration* studies at the post harvest of wheat crop in rice-wheat sequence for two years showed that the treatment of deep tillage (T_4) always favoured greater water entry into the soil profile as compared to all the other treatments. The hydraulic resistance at surface layers of T_1 may be because of a built up of 'ρ_b', which impeded water entry to a greater extent resulting into low infiltration in this treatment.

The weekly soil temperature in both wheat crop seasons during 2002-03 and 2003-04 indicated that deep/conventional tillage had slightly higher minimum temperature at 0630 hours and lower maximum temperature at 1430 hours compared to no tillage in 0.05 and 0.1 m soil depth as compared to no tillage.

In both the years of study, the emergence count per m^2, seedling emergence parameters, plant height, number of tillers per m^2 and dry matter accumulation during both the years of experimentation was significantly higher in deep (T_4)/ conventional tillage (T_2 and T_3) as compared to no-tillage (T_1).

The root mass density (RMD), root length density (RLD), root volume density (RVD) and rooting depth (RD) values were higher in deep tillage (T_4) treatment which was followed by conventional tillage (T_2 and T_3), however, significantly lower values were recorded in no-tillage (T_1) at 30, 60, 90, 120 and 150 DAS in both the years of the study. The RMD, RLD and RVD values for the depths 0.0-0.1, 0.1-0.2 and 0.2-0.3 m were also higher in deep tillage treatment which were followed by conventional tillage, however, significantly lower values were recorded in no tillage at 90, 120 and 150 DAS in both the years of the study.

The root porosity under T_4 at three periods (90, 120 and 150 DAS) was significantly lower as compared to conventional and no tillage treatments, which resulted in higher RMD and RLD values.

The grain, straw and biological yields were significantly higher in plots where deep tillage (T_4) treatment was imposed which were followed by conventional tillage, however, significantly lower grain yields were recorded in no-tilled (T_1) plots.

Conclusion

From the results of the study entitled, "Soil-water dynamics, root growth and wheat yield in a sequentially deep tilled post-rice soil", it can be concluded that: -

- The increase in depth of tillage favourably moderated the soil physical properties, thereby, soil and plant-water relations.
- The root growth of wheat was enhanced with the increase in tillage as soil-water relations were also improved.
- With the improvement in physical properties, soil-plant-water relations, and root growth due to deep tillage, the grain and straw yields of wheat also increased significantly.

LITERATURE CITED

LITERATURE CITED

Abu Hamdeh, N.H. 2003. Effect of compaction and deep tillage on soil hydraulic and aeration properties and wheat yield. Communications in Soil Science and Plant Analysis 34: 2277-2290.

Acharya, C.L. and Bhagat, R.M. 1984. Infiltration behaviour, root development and yield of rainfed maize (*Zea mays* L.) under different soil management practices. Proceedings of Indian National Science Academy, Part B. 50: 441-448.

Acharya, C.L. and Prihar, S.S. 1969. Vapour losses through soil mulch at different wind velocities. Indian Journal of Agronomy 61: 666-668.

Acharya, C.L. and Sood, M.C. 1992. Effect of tillage methods on soil physical properties and water expense of rice on an acidic alfisoil. Journal of the Indian Society of Soil Science 40: 409-414.

Adachi, T. 1990. Effect of rice-soil puddling on water percolation. Transaction 14th International Congress of Soii Science. Kyota, Japan pp.146-151.

Aggarwal, G.C., Sidhu, A.S., Sekhon, N.K., Sandhu, K.S. and Sur, H.S. 1995. Puddling and N management effects on crop response in a rice-wheat cropping system. Soil and Tillage Research 36: 129-139.

Aggarwal, P., Bhardwaj, S.P. and Khullar, A.K. 1992. Appropriate tillage systems for rainfed wheat in Doon Valley. Annals of Agricultural Research 13: 166-173.

Aggarwal, P., Garg, R.N., Das, D.K. and Sharma A.M.1992. Tillage and irrigation requirement for wheat grown on Typic ustochrepts. Indian Journal of Soil Conservation 25: 228-232.

Aggarwal, P., Parashar, D.K, Kumar, V. and Gupta, R.P. 1997. Effect of *Kharif* green manuring and tillage on physical properties of puddled clay loam under rice-wheat rotation. Journal of the Indian Society of Soil Science 45: 434-438.

Aggarwal, P.K., Talukdar, K.K. and Mall, R.K. 2000. Potential yields of rice-wheat system in the Indo-Gangetic Plains of India. Rice-Wheat Consortium for Indo-Gangetic Plains. New Delhi, India.

Akinci, I., Cakir, E., Topakci, M., Canakci, M. and Inan, O. 2004. The effect of subsoiling on soil resistance and cotton yield. Soil and Tillage Research 77: 203-210.

Al-Darby, A.M. and Lowery, B. 1987. Seed zone soil temperature and early corn growth with three conservation tillage systems. Soil Science Society of America Journal 51: 768-774.

Allen, R.R., Musick, J.T. and Schneider, A.D. 1995. Residual deep ploughing effects on irrigation intake for Pullman clay loam. Soil Science Society of America Journal 59: 1424-29.

Anonymous 2003-04. Agricultural and allied statistics. Fertilizer Statistics pp. I-266-287.

Anonymous 2004-05. Economic Survey of Himachal Pradesh. Department of Economic and Statistics, Shimla.

Arora, V.K., Gajri, P.R. and Prihar, S.S. 1991. Tillage effects on corn in sandy soils in relation to water retentivity, nutrient and water management and seasonal evaporativity. Soil and Tillage Research 21: 1-21.

Bajpai, R.K. and Tripathi, R.P. 2000. Evaluation of non-puddling under shallow water tables and alternative tillage methods on soil and crop parameters in a rice-wheat system in Uttar Pradesh. Soil and Tillage Research 55: 99-106.

Barley, K.P. 1970. The configuration of the root system in relation nutrient uptake. Advances in Agronomy 22: 159-201.

Barraclough, P.B. and Weir, A.H. 1988. Effect of a compacted subsoil layer on root and shoot growth, water use efficiency and nutrient uptake of winter wheat. Journal of Agricultural Science 110: 207-216.

Barzegar, A.R., Asoodar, M.A., Eftekhar, A.R. and Herbert, S.J. 2004. Tillage effects on soil physical properties and performance of irrigated wheat and clover in semi-arid region. Journal of Agronomy 3: 237-242.

Belford, R.K. 1981. Response of winter wheat to prolonged water-logging under outdoor conditions. Journal of Agricultural Science 97: 557-568.

Belford, R.K., Christian, D.G., Cannell, R.Q. and Goss, M.J. 1984. Drainage, cultivation and growth of winter cereals in clay soils. *In*: Fonctionnement hybrique et Comportment des sols. Association Franciase pour l'Etu du sol (AFES), Plaisir, France pp. 167-174.

Bennie, A.T.P. and Botha, F.J.P. 1985. The water uptake by maize and wheat. III. The rate of soil water supply as affected by rooting depth and density in the field. Proceedings of the 15th Annual Congress of the South African Society of Crop Production Pietermaritzburg, South Africa: 1-28.

Bhagat, R.M. 1982. Field determination of hydraulic properties and their use in measuring water withdrawal patterns by crop roots under different soil management practices, Ph.D. thesis, Department of Soil Science, Himachal Pradesh Krishi Vishvavidyalaya, Palampur (H.P.) India.

Bhagat, R.M. 1987. Infiltration characteristics of some hill soils of lower Dhauladhar ranges of Himachal Pradesh. Indian Forester 47: 222-227.

Bhagat, R.M. and Acharya, C.L. 1987. Effect of soil management on rainfed rice in northern India. I. Hydrothermal regime and root growth. Soil and Tillage Research 9: 65-77.

Bhagat, R.M. and Acharya, C.L. 1988. Soil water dynamics during wheat growth under different management practices. Journal of Indian Society of Soil Science 36: 389-396.

Bhagat, R.M. and Chand, S. 1994. Effect of management of an Himalayan alfisol on water conservation for rainfed crops. Soil and Tillage Research 28: 203-212.

Bhagat, R.M. and Verma, T.S. 1991. Impact of rice straw management on soil physical properties and wheat yield. Soil Science 152: 108-115.

Bhagat, R.M., Mangotra, M. and Sharma, P.K. 1999. Tillage effects on soil physical properties and yield of rainfed rice (*Oryza sativa* L.). Journal of the Indian Society of Soil Sciences 47: 415-421.

Bhagat, R.M., Sharma, P.K. and Verma, T.S. 1994. Tillage and residue management effects on soil physical properties and rice yields in northwestern Himalayan soils. Soil and Tillage Research 29: 327-334.

Bhushan, L. and Sharma, P.K. 1997. Effect of soil moisture regime and nutrient supplies on root growth and yield of wheat in a subsurface compacted soil. Journal of the Indian Society of Soil Science 45: 213-219.

Bhushan, L. and Sharma, P.K. 1999. Effect of depth, bulk density and aeration status of root zone on productivity of wheat. Journal of the Indian Society of Soil Science 47: 29-34.

Black, C.A. 1965. Method of Soil Analysis. Part II. American Society of Agronomy, Wisconsin, USA pp. 1572.

Bolton, F.R. and De Datta, S.K. 1979. Dry soil mulching in tropical rice. Soil Science and Plant Nutrition 25: 173-181.

Bonne, F.R. 1988. Weather and other environmental factor influencing crop responses to tillage and traffic. Soil and Tillage Research 11: 283-324.

Boparai, B.S., Singh, Y. and Sharma, B.D. 1992. Effect of green manuring with *Sesbania aculeate* on physical properties of soil and on growth of wheat in rice-wheat and maize-wheat cropping systems in a semi-arid region of India. Arid Soil Research Rehabilitation 6: 135-143.

Bordovsky, D.G., Choudhary, M. and Gerard, C.J. 1999. Effect of tillage, cropping, and residue management on soil properties in the Texas Rolling Plains. Soil Science 164: 331-340.

Brar, S.S, Kumar, S., Narang, R.S. 2000. Effect of moisture regime and nitrogen on decomposition of combine harvested rice (*Oryza sativa*) residue and performance of succeeding wheat (*Triticum aestivum*) in rice-wheat system in Punjab. Indian Journal of Agronomy 45: 458-462.

Burwell, R.E., Allmaras, R.R. and Sloneker, L.L. 1966. Structural alternation of soil surface by tillage and rainfall. Journal of Soil water Conservation 21: 61-63.

Busscher, W.J. and Bauer, P.J. 2003. Soil strength, cotton root growth and lint yield in a southeastern USA coastal loamy sand. Soil and Tillage Research 74: 151-159

Busscher, W.J., Fredrick, J.R. and Bauer, P.J. 2000. Timing effects of deep tillage on penetration resistance and wheat and soybean yield. Soil Science Society of America Journal 64: 999-1003.

Cai, S.B. and Cao, Y. 1987. Effect of water-logging and high temperature on senescence in wheat leaves during booting stage. Jiangsu Academy of Agricultural Sciences. Journal of Agricultural Science 3: 45-47.

Campbell, J.A. and Akhtar, M.E. 1990. Impact of tillage on soil water regimes in the rainfed areas of Pakistan. Proceedings: International Symposium on Applied Soil Physics in Stress Environment, 22-26 January. Islamabad, Pakistan, pp. 267-275.

Cannell, R.Q., Belford, R.K., Gales, K., Thompson, R.J. and Webster, O.P. 1984. Effect of water-logging and drought on winter wheat and winter barley grown on a clay and sandy loam soil. I. Crop growth and yield. Plant and Soil 80: 53-66.

Carefoot, J.M., Nyborg, M. and Lindwall, C.W. 1990. Tillage induced soil change and related grain yield in a semi-arid region. Canadian Journal of Soil Science 70: 203-214.

Carlson, C.W. 1978. In modification of soil structure (W.W. Emerson *et al.* Editors) John Wiley and Sons. New York pp. 279-284.

Chang, C. Lindwall, C.W. 1992. Effects of tillage and crop rotation on physical properties of a loam soil. Soil and Tillage Research 22: 383-389.

Chaudhary, R.S. and Acharya, C.L. 1993. A comparison of evaporative losses from soil of different tilths and under mulch after harvest of rice. Soil and Tillage Research 28: 191-199.

Chenkual, V. and Acharya, C.L. 1990. Effect of rice-wheat and maize-wheat rotations on soil physical properties including soil behaviour in an acidic Alfisol. Journal of the Indian Society of Soil Science 38: 574-582.

Cochran, W.G. and Cox, G.M. 1963. Experimental Designs. Asia Publishing House, New Delhi.

Collis-George, N. 1980. A pragamatic method to determine the parameters that characterize ponded infiltration. Australian Journal of Soil Research 18: 111-117.

Das, N.R. and Mukherjee, N.N. 1995. Tillering behaviour of irrigated dwarf wheat under tillage and NPK fertilizer, after rice. Advances in Agricultural Research in India 3: 1-10.

Dass, N.R. and Kashyapi, A. 1992. Effect of hoeing and seeding depth on yield of irrigated wheat after transplanting wet rice in Entisol. Indian Journal of Agronomy 37: 577-579.

Dobermann, A. and Cassman, K.G. 1996. Precision nutrient management in intensive rice systems- The need for another on-farm revolution. Better Crops 10: 20-25.

Drury, C.F., Tan, Chin-Sheng, Welacky, T.W, Oloya, T.O., Hamill, A.S. and Weaver, S.E. 1999. Red clover and tillage influence on soil temperature, water content, and corn emergence. Agronomy Journal 91: 101-108.

Ehrler, W.L., khosla, B.K., Kopke, V., Stulfuagel, R., Bohm, W. and Baeumer, K. 1980. Tillage effects on root development, water uptake and growth of oats. Soil and Tillage Research 1: 19-34.

Ferreras, L.A., Costa, J.L., Garcia, F.O., Pecorari, C. 2000. Effect of no-tillage on some soil physical properties of a structural degraded Petrocalcic Paleudoll of the southern "Pampa" of Argentina. Soil and Tillage Research 54: 31-39.

Fortin, M.C. and Pierce 1990. Development and growth effects of crop residues on corn. Agronomy Journal 82: 710-715.

Fortin, M.C. and Pierce 1991. Timing and nature of mulch retardation of corn vegetative development. Agronomy Journal 83: 258-263.

Fujisaka, S., Harrington, L. and Hobbs, P.R. 1994. Rice-wheat in South Asia: Systems and long-term priorities established through diagnostic research. Agricultural University, Hissar, India pp. 61-76.

Gajri, P. R., Prihar, S.S., Cheema, H.S. and Kapoor, A. 1991. Irrigation and tillage effects on root development, water use and yield of wheat on coarse-textured soils. Irrigation Science 12: 161-168.

Gajri, P.R., Jasbir, Singh, Arora, V.K., Gill, B.S. and Singh, J. 1997. Tillage responses of wheat in rotation to irrigation regimes and nitrogen rate on an alluvial sand in semi-arid sub-tropical climates. Soil and Tillage Research 42: 33-36.

Gangwar, K.S., Singh, K.K. and Sharma, S.K. 2004. Effect of tillage on growth, yield and nutrient uptake in wheat after rice in the Indo-Gangetic Plains of India. Journal of Agricultural Science 142: 453-459.

Gardner, W.R. 1964. Relation of root distribution to water uptake and availability. Agronomy Journal 56: 41-45.

Garvitech, Z.S. and Probine, M.C. 1956. Soil Thermocouples. Nature 1177: 1245.

Gill, K.S., Jalota, S.K., Prihar, S.S. and Chaudhary, T.N. 1977. Water conservation by soil mulch in relation to soil types, time of tillage, tilth and evaporativity. Journal of Indian Society of Soil Science 25: 360-366.

Gregory, P.J., Mc Gowan, M. and Biscoe, P.V. 1978. Water relations in winter wheat. 2. Soil water relations. Journal of Agricultural Science Cambridge 91: 103-116.

Gupta, J.P. 1987. Effect of tillage and mulch on soil and the growth and yield of wheat grown in the arid tropics. Arid Soil Research Rehabilitation 1: 161-172.

Gupta, P.R. and Jaggi, I.K. 1979. Soil physical conditions and paddy yield as influenced by depth of puddling. Journal of Agronomy and Crop Science 146: 329-336.

Gupta, S.C., Schneider, E.C. and Swan J.B. 1988. Planting depth and tillage interactions on corn emergence. Soil Science Society of America Journal 52: 1122-1127.

Guyot, C. and Prioul, J.L. 1985. Alleviation of water-logging effects in winter wheat by mineral fertilizer application. I. Experiment on Soil. Agronomy 5: 743-750.

Hajabbasi, M.A. 2001. Tillage effects on soil compactness and wheat root morphology. Journal of Agricultural Science and Technology 3: 67-77.

Hall, D.J.M., Mckeuzie, D.C., Maclead, D.A. and Toole, I.D. 1994. Amelioration of a hard setting Alfisol through deep mouldboard ploughing, gypsum application and double cropping. III. Crop production and profitability. Soil and Tillage Research 28: 287-300.

Hanway, J. and Heidal, H.S. 1952. Soil testing laboratory procedure. Iowa Agriculture 57: 1-31.

Hasegawa, S., Thangaraj, M. and O'Tool, J.C. 1985. Root behaviour: Field and laboratory studies for rice and non-rice crops. *In*: Soil Physics and Rice. IRRI, Los Banos, Philippines pp.383-395.

Hillel, D., Krentos, V.D. and Slytranon, V. 1972. Procedure and test of an internal drainage method for measuring soil hydraulic characteristics *in situ*. Soil Science 114: 395-400.

Hobbs, P.R. 1994. Rice-wheat system in South Asia. *In*: Proceeding Symposium on Sustainability of rice-wheat cropping in India. Haryana Agricultural University, Hissar, India pp 61-76.

Hobbs, P.R., Harrington, L.W., Adhikari, G.S., Upadhya, S.R. and Adhikari, B. 1996. Wheat and rice in Nepal Tarai: Farm resources and production practices in Rupandehli District. Nepal Agriculture Research Council and CIMMYT, Mexico.

Holloway, R.E. and Dexter, A.R. 1991. Tillage and compaction effects on soil properties, root growth and yield of wheat during drought in a semi-arid environment. Soil Technology 4: 233-253.

IRRI, 1992. IRRI Repertor. International Rice Resources Institute, Los Bano's, Philippines. 4/92:4.

Ishaq, M., Ibrahim, M. and Lal, R. 2002. Tillage effects on soil properties at different levels of fertilizer application in Punjab, Pakistan. Soil and Tillage Research 68: 93-99.

Ishaq, M., Ibrahim, M. and Lal, R. 2003. Tillage and fertilizer effects on root growth of wheat and cotton on a sandy clay loam in Pakistan. Journal of Sustainable Agriculture 22: 43-57.

Jackson, M.L. 1967. Soil Chemical Analysis. Prentice Hall, India Private Limited New Delhi.

Jensen, C.R., Luxmoore, R.J., Van Gundy, S.D. and Stolzy, L.H. 1969. Root air space measurement by a Pycnometer method. Agronomy Journal 61: 474-478.

Jones, H.P., Allen, R.R. and Unger, P.W. 1990. Tillage systems and equipment for dryland farming. Advances in Soil Science 13: 89-130.

Khakural, B.R., Lemme, G.D., Schumocher, T.E. and Lindstrom, M.J. 1992. Effects of tillage systems and landscape on soil. Soil and Tillage Research 25: 43-52.

Khan, B.R. and Raja, S.H. 1989. Effect of tillage and water harvesting techniques on the yield of cereals and food legumes under rainfed conditions. Sarhad Journal of Agriculture 5: 331-335.

Khan, M.S., khan, T.H., Islam, A., Ullah, M.S. and Shara, R.R. 1998. Effect of alternate practices on rooting characteristics of wheat under rice-wheat sequence. Annals of Bangladesh Agricultural 7: 111-118.

Kisu, M. 1978. Tillage properties of wet soils. *In*: Soil Physics and Rice, The International Rice Research Institute, Los Banos, Philippines pp. 307-316.

Klepper, B., Taylor, H.M., Huck, M.G. and Fiscus, E.L. 1973. Water relations and growth of cotton in drying soils. Agronomy Journal 65: 307-310.

Klute, C.J. 1965. Laboratory measurement of hydraulic conductivity of saturated soil. *In*: C.A. Black (Ed.). Methods of Soil Analysis, Part I. pp. 210-220.

Kopke, U. 1979. Ein Vergleich von feldmethoden zur bestimmungdes Wurrzelwachstums bei landwirtschefllichen Kullurpflanzen. Diss. Agric. Gottingen, 1979.

Kostiakov, A.N. 1932. On the dynamics of the co-efficient of water percolation in soils and the necessity for studying it from a dynamic view for purposes of ameliorations. Transaction 6th Congress International Society of Soil Science. Russian Part A: 17-21.

Kumar, V., Mahajan, K.T., Varade, S.V. and Ghildyal, B.P. 1971. Growth response of rice (*Oryza sativa* L.) to submergence, soil aeration and soil strength. Indian Journal of Agricultural Sciences 41: 527-534.

La Rue, M.E., Nielsen, D.R. and Hagan, R.M. 1968. Soil water flux below a rye grass root zone. Agronomy Journal 60: 625-629.

Ladha, J.K., Dawe, D., Pathak, H., Padre, A.T., Yadav, R.L., Singh, B., Singh, Y., Singh, P., Kundu, A.L., Sakal, R., Ram, N., Regmi, A.P., Gami, S.K., Bhandhari, A.L., Amin, R., Yadev, C.R., Bhattarai, E.M., Das, S., Aggarwal, H.P., Gupta, R.K. and Hobbs, P.R. 2003a. How extensive are yield declines in long term rice-wheat experiments in Asia? Field Crops Research (in press).

Ladha, J.K., Fischer, K.S., Hossain, M., Hobbs, P.R., and Hardy (ed.) 2000. Improving the productivity and sustainability of rice- wheat systems of the Indo-Gangetic Plains: A synthesis of NARS-IRRI partnership research. Discussion Paper 40. IRRI, Los Banos, Philippines.

Lal, R. 1991. Tillage and agricultural sustainability. Soil and Tillage Research 20: 133-146.

Majumdar, S.P. 1994. Soil physical constraints and their management in Rajasthan. Technical Bulletin of Rajasthan Agricultural University, Jobner Campus, Rajasthan.

Marsh, B.B. 1971. Measurement of length in random arrangement of lines. Journal of Applied Ecology 8: 256-257.

Mc Gowan, M. 1971. Depths of water extraction by roots. Application to soil water balance studies. In isotopes and radiation techniques in Soil Physics and Irrigation Studies (1973) pp. 435-445.

Meelu, O.P., Beri, V., Sharma, K.N. Jalota, S.K. and Sandhu, B.S. 1979. Influence of paddy and corn in different rotations on wheat yield, nutrient removal and soil properties. Plant and Soil 51: 51-57.

Mehta, R.K., Singh, G., Rajput, A.L., Singh, O.P. 1996. Response of late sown wheat to tillage practices after flood prone rice. Annals of Agricultural Research 17: 9-13.

Meyer, W.S. and Barrs, H.D. 1988. Response of wheat to single short-term water-logging during and after stem elongation. Australian Journal of Agricultural Research 39: 11-20.

Mielke, L.D., Doran, J.W. and Richard, K.A. 1986. Physical environment near the surface of plowed and no-tilled soil. Soil and Tillage Research 7: 355-366.

Mishra, R.D. and Ahmed, M. 1987. Manual on Irrigation Agronomy. Oxford and IBH Publishing Company Private Limited, New Delhi pp. 319-326.

Murty, N.S., Singh, R.K. and Arya, M.P.S. 2004. Effect of different land management practices on moisture conservation and yield of wheat in the mid Himalayan region of Uttaranchal. Journal of Agrometeorology 6: 238-241.

Newman, W.W. 1966. A method of estimating the total length of root in a sample. Journal of Applied Ecology 3: 139-145.

Ogata, G., Richards, L.A. and Gardner, W.R. 1960. Transpiration of alfalfa determined from soil water content changes. Soil Science 89: 179-182.

Ojeniyi, S.O. and Dexter, A.R. 1979. Soil factors affecting the micro-structure produced by tillage. Transaction American Society of Agricultural Engineering 22: 339-343.

Olsen, S.R., Cole, C.V., Watanabe, F.S. and Dean, L.A. 1954. Estimation of available phosphorous by extraction with sodium bicarbonate. United State Department of Agriculture Circular 939 pp.19-23.

Orellana, K., Barber, R.G. and Diaz, O. 1990. Effects of deep tillage and fertilization on population, growth and yield of soya during on exceptionally wet season in a compacted sandy loam, Sonta Curz. Bobina. Soil and Tillage Research 17: 47-61.

Padma Raju, A. and Dev, A.R. 1969. Influence of crop rotation on the structure of paddy soils. Indian Journal of Agricultural Sciences 39: 81-87.

Pathak, H., Ladha, J.K., Aggarwal, P.K., Peng, S., Das, S., Singh, Y., Singh, B., Kamra, S.K., Mishra, B., Sastri, A.S.R.A.S., Aggarwal, H.P., Das, D.K. and Gupta, R.K. 2003. Climatic potential and on-farm yield trends of rice and wheat in Indo-Gangetic Plains. Field Crop Research (in press).

Pelegrin, F., Morena, F., Martin- Aranda, J. and Campus 1990. The influence of tillage methods on soil physical properties and water balance for a typical crop rotation in SW Spain. Soil and Tillage Research 16: 345-358.

Peterson, C.M., Kleeper, B., Pumphery, F.V. and Rickmen, R.W. 1984. Restricted rooting decreases tillering and growth of winter wheat. Indian Journal of Agronomy 76: 863-865.

Philip, J.R. 1957. The theory of infiltration: 4. Sorptivity and algebraic infiltration equation. Soil science 83: 345-357.

Pikul, J.L. and Aase J.K. 1999. Wheat response and residual soil properties following subsoiling of a sandy loam in eastern Montana. Soil and Tillage Research 51: 61-70.

Pillai, K.G., 1994. Current trends in production and productivity and improving rice production. *In*: S.D. Dhimal, M.K. Choudhary, D.V.S. Panwar and K.S. Verma (Editors). Proceeding of symposium on sustainability of rice-wheat cropping in India. CCS HAU, Hissar, India. Pp. 14-60.

Piper, C.S. 1966. Soil and Plant Analysis. Hans Publisher Bombay, India pp. 223- 227.

Pot, M. and Ouwerkerk, C. VAN 1980. Conventional tillage and minimum tillage in a wide crop rotation. Annual Report, 1977, Haren, Netherlands.

Prihar, S. S., Gajri, P. R., Benbi, D. K. and Arora, V. K. 2000. In *Intensive Cropping*: Efficient use of water, nutrients and tillage, The Haworth Press, Binghamton, New York, U.S.A.

Prihar, S.S., Ghildyal, B.P., Painuli, D.K. and Sur, H.S. 1985. Physical properties of mineral soils affecting rice-based cropping systems. *In*: Soil Physics and Rice. IRRI, Los Banos, Philippines pp. 57-70.

Prihar, S.S., Khapra, S.D., Singh, R., Grewal, S.S. and Sodhi, S.K. 1990. Water resources of Punjab- A critical concern for the future of its agriculture. Punjab Agricultural University, Ludhiana, India.

Prihar, S.S., Khera, K.K. and Gajri, R.R. 1975. Effect of puddling with different implements on the water and yield of paddy. Journal of Research 13: 249-254.

Prihar, S.S., Singh, B. and Sandhu, B.S. 1968. Influence of soil and climatic environments on evaporative losses from mulched and un-mulched plots. Punjab Journal of Agricultural Research 5: 320-328.

Rahman, S.M. 1991. Tillage effects on some physical properties. Annals of Agriculural Research 12: 196-199.

Rao, M.S.R.M. and Kathavate, Y.V. 1972. Effect of soil compaction on the yield of wheat and maize. Indian Journal of Agronomy 17: 199-205.

Regmi, A.P., Ladha, J.K., Pathak, H., Pasuquin, E., Bueno, C., Dawe, D., Hobbs, P.R., Joshy, D., Maskey, S.L. and Pandey, S.P. 2002. Yield and soil fertility trends in a 20 year rice-wheat experiment in Nepal. Soil Science Society of America Journal 66: 857-867.

Sandeep, K., Pandey, D. S. and Rana, N. S. 2004. Wheat yield and soil bulk density response to tillage, residue and nitrogen management under rice-wheat system. Annals of Agricultural Research 25: 113-117.

Sawhney, J.S. and Sehgal, J.L. 1989. Effect of rice-wheat and maize-wheat crop rotations on aggregation, bulk density and infiltration characteristics of some alluvium derived soils. Journal of the Indian Society of Soil Science 37: 235-239.

Shafiq, H., Hassan, A., Ahmad, M. and Rashid, A. 1994. Crop yields and nutrient uptake by rainfed wheat and moongbean as affected by tillage, fertilization and weeding. Journal of Plant Nutrition 17: 561-577.

Sharad, N. and Verma, T.S. 2001. Improvement in soil productivity with long term lantana (*Lantana camara* L.) additions in rice-wheat cropping. I. Effects on some properties and zinc fractions. Journal of the Indian Society of Soil Science 49: 462-466.

Sharma, B.R. 1991. Effect of different tillage practices mulch and nitrogen on soil properties, growth and yield of fodder maize. Soil and Tillage Research 19: 55-56.

Sharma, J.C. and Acharya, C.L. 1993. Root water uptake as influenced by nitrogen and tillage. Journal of Water Management 1: 12-16.

Sharma, P.K. and Bhagat, R.M. 1993a. Puddling and compaction effects on water permeability of texturally different soils. Journal of the Indian Society of Soil Science 41: 1-6.

Sharma, P.K. and Bhagat, R.M. 1993b. A simple apparatus for measuring clod breaking strength. Journal of the Indian Society of Soil Science 41: 422-425.

Sharma, P.K. and De Datta, S.K. 1985. Puddling influence on soil, rice development and yield. Soil Science Society of America Journal 49: 1451-1457.

Sharma, P.K. and De Datta, S.K. 1986. Physical properties and processes of puddle rice soils. Advances in Soil Science 5: 139-178.

Sharma, P.K. and Kharwara, P.C. 1994. Effect of tillage and weed control on wheat yield in a sandy loam soil under irrigated and rainfed conditions. Himachal Journal of Agricultural Research 20: 28-34.

Sharma, P.K. and Verma, T.S. 2001. Dynamics of nitrogen fractions with long-term additions of *Lantana camara* biomass in rice-wheat cropping sequence. Journal of the Indian Society of Soil Science 49: 407-412.

Sharma, P.K., De Datta, S.K. and Redulla, C.A. 1988. Tillage effects on soil physical properties and wet-land rice yield. Agronomy Journal 80: 34-39.

Sharma, P.K., Ladha, J.K and Bhushan, L. 2003. Soil physical effects of puddling in rice-wheat cropping systems. Improving the productivity and sustainability of rice-wheat systems: Issues and impacts. ASA Special Publications 65.

Sharma, P.K., Verma, T.S. and Bhagat, R.M. 1995. Soil structural improvement with the addition of *Lantana camara* biomass in rice-wheat cropping. Soil Use and Management 11: 199-203.

Sharma, R.B., Verma, G.P. and Russell, M.P. 1971. Effect of varying bulk densities of surface and sub-surface soil on wheat growth under field conditions. Indian Society of Soil Science 1: 519-527.

Singh, P., Aipe, K.C., Prasad, R., Sharma, S.N. and Singh, S. 1998. Relative effect of zero and conventional tillage on growth and yield of wheat and soil fertility under rice-wheat cropping system. Indian Journal of Agronomy 43: 204-207.

Singh, P.K. and Singh, Y. 1996. Effect of reduced tillage on soil physical properties, root growth on grain yield in rice-wheat system. Indian Journal of Agricultural Research 30: 179-185.

Singh, R.A. 1980. Soil Physical Analysis. Kalayani Publishers, New Delhi pp. 165.

Singh, Y. 1995. Rice-wheat system: status, resource and concern. *In*: Summer Institute on Integrated Nutrient Management in Intensive Cropping System, June 22- July 11, 1995 pp. 307-314.

Subbiah, B.W. and Asija, G.L. 1956. A rapid procedure for the estimation of available nitrogen in soils. Current Science 25: 259-260.

Sur, H.S., Prihar, S.S. and Jalota, S.K. 1981. Effect of rice-wheat and maize-wheat rotations on water transmission and wheat root development in a sandy loam soil of Punjab, India. Soil and Tillage Research 1: 361-371.

Taylor, H.M. 1972. Effect of drying on water retention of a puddle soil. Soil Science Society of America Proceeding 36: 972-973.

Tennant, D. 1975. A test of a modified line intersect method of estimating root length. Journal of Applied Ecology 63: 995-1001.

Thakur, R.C., Sood, R.D., Bhargava, N. and Chaudhary, J.B. 1994. Present status and future strategies for research in rice-wheat cropping systems in Himachal Pradesh. *In*: Proceedings of symposium on sustainability of Rice-Wheat Cropping system in India. CCS Haryana Agricultural University, Hissar, India pp. 9-17.

Thompson, C.A. 2001. Winter wheat and grain production as influenced by depth of soil water, tillage and cropping systems. Journal of Soil and Water Conservation 56: 56-63.

Titkov, A.A. and Gusev, P.G. 1989. Composition and properties of soils of rice rotation in Sivash region of Crimea. Soviet Soil Science 21: 110-116.

Tomar, R.K., Singh, J.P., Garg, R.N., Gupta, V.K., Sahoo, R.N., and Arora, R.P. 2003. Effect of weed management practices on weed growth and yield of wheat in rice based cropping system under varying levels of tillage. Annals of Plant Protection Sciences 11: 123-128.

Tomar, S.S. Russell, M.B. and Tomar, A.S. 1981. Effect of subsurface compaction on root distribution and growth of wheat. Zeitschriff fur Acker-und Pflan Zenban 150: 62-67.

Trought, M.C.T. and Drew, M.C. 1980. The development of water-logging damage in wheat seedlings (*Triticum aestivum* L.) I. Shoot and root growth in relation to change in concentration of dissolved gases and solute in the soil solution. Plant and Soil 54: 77-94.

Unger, P.W. 1979. Effect of deep tillage and profile modification on soil properties, root growth and crop yields in the United State and Canada. Geoderma 22: 275-295.

Unger, P.W. and Cassel, D.K. 1991. Tillage and implements disturbance effects on soil properties related to soil and water conservation: a literature review. Soil and Tillage Research 19: 363-382.

Unger, P.W. and Jones, O. R. 1998. Long-term tillage and cropping systems affect bulk density and penetration resistance of soil cropped to dryland wheat and grain sorghum. Soil and Tillage Research 45: 39-57.

Utomo, W.H. and Dexter, A.R. 1981. Soil friability. Journal of Soil Science 32: 303-213.

Van Bavel, C.H.M., Stirk, G.B. and Brust, K.J. 1968. Hydraulic properties of clay loam soil and the field measurement of water uptake by roots II. The water balance of root zone. Soil Science Society of America Proceedings 32: 317-321.

Verma, S.D. 1979. Characterization and genesis of soils of Himachal Pradesh, Ph.D. thesis, Department of Soil Science, Himachal Pradesh Krishi Vishvavidyalaya, Palampur (H.P.) India.

Walkely, A. and Black, C.A. 1934. An estimation of the method for determination of soil organic matter and a proposed modification of the chromic acid titration method. Soil Science 37: 29-39.

Warning, R.H. and Cleary, B.D. 1967. Plant moisture stress evaluation by pressure bomb. Science 155: 1248-1254.

Werner, D. 1988. Effect of soil physical conditions on uptake of water by agricultural crops. Archir fiir Acket and Pflanzenba and Bodenkunde 32: 303-310.

Xi-Ying, Z., Dong, P. and Su-Ying, C 2004. Root growth and soil water utilization of winter wheat in the North China Plain. Hydrological Processes 18: 2275-2287.

Yadav, R.L. 1996. Cropping systems. *In*: 50 years of Crop Science Research in India, ICAR Publications pp. 117-120.

Yadav, R.L. and Subba Rao, A.V.M 2001. Atlas of cropping systems in India. PDCSR Bulletin No. 2001-02, pp. 96, PDCSR, Modipuram.

Yozar, A. 1985. The effect of tillage treatments on soil properties and maize yields. Doga Bilim Dergisi, Dz Tarim Ve Ormancilik 9: 221-230.

Yun-Sheng, C. 1983. Drainage of paddy soils in Taihu Lake region and its effects. Soil Research Report No. 8. Institute of Soil Science, Academia Sinica, Nanjing, China.

Zhao, B.Q., Li, F.C., Xue, J. and Li, Z.J. 1997. Effect of different tillage methods on root growth of winter wheat. Acta Agronomica Sinica 23: 587-596.

APPENDICES

Appendix I: Daily meteorological data of Palampur for the first wheat crop season (2002-03)

Date	$T_{(Max.)}$ ^{0}C	$T_{(Min.)}$ ^{0}C	$RH_{(Max.)}$ %	$RH_{(Min.)}$ %	WV (Km/hr)	BSS (hr)	RF (mm)	Evap. (mm)
1	2	3	4	5	6	7	8	9
24-11-02	23.5	11.0	49	40	5.5	8.3	0.0	3.9
25-11-02	23.0	9.2	50	39	4.5	5.0	0.0	4.0
26-11-02	23.5	9.2	50	34	5.1	9.5	0.0	4.2
27-11-02	23.0	7.6	49	41	5.9	9.6	0.0	4.0
28-11-02	21.5	8.5	55	40	5.0	9.0	0.0	4.0
29-11-02	21.5	7.0	47	33	5.0	9.0	0.0	3.5
30-11-02	20.5	6.0	47	38	8.4	9.5	0.0	3.0
01-12-02	20.5	6.0	47	38	8.4	9.5	0.0	3.0
02-12-02	20.5	6.5	46	43	7.3	9.4	0.0	2.8
03-12-02	20.0	6.0	52	36	5.1	9.0	0.0	3.0
04-12-02	19.5	7.3	68	52	5.0	9.1	0.0	2.8
05-12-02	18.0	8.5	69	50	5.3	6.0	0.0	2.0
06-12-02	18.0	7.0	53	50	4.0	1.0	0.0	2.0
07-12-02	18.5	6.5	43	22	5.0	9.5	0.0	2.0
08-12-02	18.5	6.0	44	24	4.4	9.5	0.0	2.0
09-12-02	19.4	6.0	40	24	9.4	8.8	0.0	2.0
10-12-02	21.5	6.5	71	29	4.8	9.8	0.0	2.7
11-12-02	20.4	8.0	47	46	5.3	5.5	0.0	3.2
12-12-02	19.0	6.0	59	32	4.5	2.8	0.0	3.0
13-12-02	20.8	8.3	46	50	5.2	6.2	0.0	3.5
14-12-02	19.8	7.0	45	49	4.8	4.8	0.0	3.3
15-12-02	19.0	6.5	51	41	5.3	5.3	0.0	3.0
16-12-02	21.5	6.5	58	49	4.9	4.6	0.0	3.0
17-12-02	20.0	8.5	54	37	4.2	3.2	0.0	3.4
18-12-02	21.5	8.5	40	30	5.8	9.2	0.0	3.8
19-12-02	21.0	9.8	58	41	6.0	6.3	0.0	3.0
20-12-02	19.0	6.5	54	35	4.0	3.6	0.0	2.2
21-12-02	19.5	8.0	37	26	6.6	8.6	0.0	2.5
22-12-02	19.5	6.0	49	26	5.3	9.8	0.0	3.0
23-12-02	19.5	6.0	42	31	5.7	9.2	0.0	3.0
24-12-02	19.5	6.0	52	49	5.6	6.4	0.0	2.0
25-12-02	19.5	6.0	55	31	4.5	3.5	0.0	2.0
26-12-02	19.5	5.5	68	63	5.2	8.4	0.0	2.0
27-12-02	19.5	3.5	73	43	4.6	4.0	0.0	2.0
28-12-02	18.0	3.0	62	55	4.7	9.0	0.0	2.0
29-12-02	16.0	3.0	55	51	4.4	2.8	0.0	1.8
30-12-02	15.5	2.5	64	26	4.3	6.0	0.0	2.0
31-12-02	16.0	2.5	72	65	4.0	1.5	0.0	2.0
01-01-03	12.0	2.0	67	56	6.1	6.8	0.0	1.5
02-01-03	13.5	3.0	70	43	5.7	4.4	0.0	1.3
03-01-03	16.5	4.5	60	55	5.3	8.0	0.0	1.2

1	2	3	4	5	6	7	8	9
04-01-03	15.5	3.5	56	56	6.9	9.3	0.0	1.4
05-01-03	16.5	6.0	53	49	6.0	9.6	0.0	1.2
06-01-03	18.5	5.0	45	33	5.9	8.0	0.0	2.0
07-01-03	18.5	2.3	61	47	5.7	9.2	0.0	2.1
08-01-03	18.5	3.5	62	33	5.1	9.3	0.0	2.2
09-01-03	17.2	4.0	45	35	5.3	9.3	0.0	2.1
10-01-03	17.5	3.5	56	27	5.4	9.4	0.0	2.2
11-01-03	18.0	4.0	49	26	7.5	9.0	0.0	2.2
12-01-03	17.0	3.5	44	29	5.8	9.2	0.0	2.3
13-01-03	16.0	3.5	43	19	6.1	9.0	0.0	2.4
14-01-03	18.6	3.0	44	22	5.4	9.5	0.0	3.0
15-01-03	18.6	5.0	34	30	7.3	9.3	0.0	3.2
16-01-03	18.0	5.0	37	27	5.4	8.5	0.0	2.6
17-01-03	19.5	5.5	37	27	5.7	5.6	0.0	2.0
18-01-03	19.5	5.0	53	38	4.9	6.5	0.0	2.8
19-01-03	19.4	6.6	30	33	4.0	3.1	0.0	2.3
20-01-03	18.5	6.0	43	36	5.7	8.5	0.0	2.0
21-01-03	19.5	6.0	30	33	5.6	9.3	0.0	2.0
22-01-03	19.8	6.0	36	28	5.0	8.2	0.0	2.2
23-01-03	19.5	6.0	37	23	6.0	9.1	0.0	2.4
24-01-03	19.6	5.5	42	27	4.7	9.4	0.0	2.8
25-01-03	18.6	5.5	52	31	8.0	9.2	0.0	2.9
26-01-03	20.0	7.8	56	24	4.5	8.8	0.0	3.3
27-01-03	20.2	10.0	38	36	7.2	4.0	0.0	4.0
28-01-03	20.0	6.5	93	87	6.5	5.0	4.0	3.5
29-01-03	20.2	4.5	88	62	6.7	0.0	15.9	2.0
30-01-03	15.0	6.5	87	97	4.2	6.3	0.0	2.6
31-01-03	10.0	6.0	91	94	5.5	0.0	4.3	1.8
01-02-03	11.0	4.0	86	74	4.5	0.0	16.6	1.5
02-02-03	12.0	5.0	74	59	6.7	2.0	7.2	1.8
03-02-03	15.0	5.0	64	40	5.7	5.6	0.0	1.8
04-02-03	16.8	5.5	66	44	6.2	9.9	0.0	2.9
05-02-03	18.5	6.5	64	35	5.1	9.9	0.0	3.8
06-02-03	18.5	7.5	51	45	6.1	10.2	0.0	3.5
07-02-03	18.0	7.5	55	56	5.7	8.4	0.0	2.0
08-02-03	17.5	6.0	61	76	4.6	8.0	0.0	2.8
09-02-03	18.0	6.0	73	80	5.3	5.0	0.0	2.0
10-02-03	18.0	5.0	65	45	5.7	8.5	0.0	2.0
11-02-03	17.6	5.0	67	54	5.4	10.3	0.0	2.0
12-02-03	17.5	5.5	70	47	5.9	9.0	0.0	3.2
13-02-03	16.5	5.5	55	44	5.7	8.3	0.0	3.0
14-02-03	16.5	6.0	58	37	5.1	8.8	0.0	3.0
15-02-03	17.6	7.0	64	32	7.0	9.0	0.0	2.8
16-02-03	19.5	7.0	87	85	7.4	7.2	1.6	2.2
17-02-03	18.0	8.0	60	73	11.3	0.0	0.4	2.0
18-02-03	15.0	7.5	90	10	13.0	0.0	12.4	1.8

1	2	3	4	5	6	7	8	9
19-02-03	12.5	2.0	92	82	11.9	0.0	34.0	1.6
20-02-03	12.6	2.2	85	58	8.6	2.0	2.1	1.8
21-02-03	13.5	5.0	48	35	6.2	7.0	0.0	2.2
22-02-03	17.5	5.0	44	47	6.1	10.0	0.0	3.8
23-02-03	19.0	5.0	87	59	5.8	9.0	2.0	3.0
24-02-03	19.5	5.0	80	66	4.3	0.8	1.6	1.8
25-02-03	19.0	5.5	77	42	4.8	6.0	0.0	2.8
26-02-03	21.0	9.5	56	43	4.3	9.0	0.0	3.5
27-02-03	21.5	11.0	60	39	5.0	6.5	0.0	3.2
28-02-03	22.0	11.5	56	37	9.6	6.0	0.3	2.8
01-03-03	16.0	7.0	87	93	6.5	5.0	20.8	3.5
02-03-03	19.0	8.5	93	75	9.9	0.0	26.4	1.6
03-03-03	19.0	8.5	75	44	10.4	3.7	18.9	2.5
04-03-03	19.0	5.0	78	56	5.5	5.0	0.0	1.8
05-03-03	16.8	3.0	56	44	6.3	5.3	0.0	2.2
06-03-03	17.8	5.0	65	37	6.5	10.0	0.0	3.3
07-03-03	18.0	6.5	49	34	6.3	10.0	0.0	3.2
08-03-03	19.6	6.0	40	32	7.1	10.2	0.0	3.8
09-03-03	19.0	6.5	48	38	6.7	7.3	0.0	3.3
10-03-03	20.2	10.0	70	32	8.0	0.1	0.0	3.2
11-03-03	22.2	9.0	39	34	7.1	3.5	0.0	4.0
12-03-03	22.0	10.0	40	33	6.0	10.3	0.0	4.0
13-03-03	22.0	9.5	52	38	7.6	8.0	1.7	3.8
14-03-03	20.5	10.0	39	40	6.3	8.5	0.0	3.8
15-03-03	20.5	10.0	56	40	4.7	1.5	0.0	2.0
16-03-03	23.5	10.0	35	30	7.5	8.0	0.0	2.0
17-03-03	24.0	7.5	48	30	14.1	6.0	6.0	2.0
18-03-03	24.0	8.0	49	40	13.0	7.5	4.0	2.0
19-03-03	24.0	8.0	44	31	5.4	7.0	0.0	2.5
20-03-03	24.0	9.0	48	41	4.6	10.4	0.0	3.2
21-03-03	24.0	10.5	45	35	6.6	10.4	0.0	4.0
22-03-03	24.2	12.5	43	42	7.9	10.5	0.0	4.2
23-03-03	26.0	12.0	43	31	7.6	6.8	0.0	4.1
24-03-03	25.0	13.0	44	37	7.0	7.4	0.0	3.3
25-03-03	25.5	13.5	47	63	5.7	6.2	0.0	3.5
26-03-03	25.5	12.0	57	43	6.4	0.2	0.0	4.0
27-03-03	23.0	13.0	57	28	5.9	7.8	0.0	3.2
28-03-03	23.5	12.5	50	47	5.4	9.0	0.0	3.5
29-03-03	23.0	8.2	75	33	9.1	3.3	0.2	3.0
30-03-03	20.5	10.5	70	79	5.7	0.1	3.6	2.7
31-04-03	15.0	23.0	59	45	9.1	2.0	9.6	1.5
01-04-03	10.0	12.0	35	41	70.0	0.0	0.0	1.2
02-04-03	24.0	12.0	42	45	9.4	9.7	2.5	3.0
03-04-03	24.5	13.0	67	41	5.6	5.5	1.3	2.9
04-04-03	24.5	12.5	48	43	10.9	2.6	2.4	3.1
05-04-03	23.5	9.0	44	41	7.5	6.0	9.0	2.9

1	2	3	4	5	6	7	8	9
06-04-03	23.0	10.5	42	40	7.6	9.9	0.0	3.5
07-04-03	24.8	12.5	54	39	7.4	11.0	0.0	4.4
08-04-03	26.0	13.0	47	39	5.1	11.0	0.0	5.2
09-04-03	26.5	15.0	51	42	7.3	11.0	0.0	4.8
10-04-03	28.0	16.5	48	31	4.5	11.0	0.0	4.8
11-04-03	29.5	16.5	42	35	4.7	11.0	0.0	5.2
12-04-03	28.5	16.0	44	44	10.2	11.2	0.0	5.0
13-04-03	26.3	16.2	48	46	7.6	10.5	0.0	4.2
14-04-03	25.0	13.2	43	38	9.1	6.8	0.8	3.0
15-04-03	24.5	13.6	49	44	6.9	6.0	0.0	4.4
16-04-03	25.5	15.0	70	39	7.6	4.0	0.6	3.4
17-04-03	23.8	16.0	53	38	6.5	5.0	0.7	3.6
18-04-03	23.8	15.4	55	51	5.8	11.0	0.0	3.8
19-03-03	24.5	1.0	46	54	7.4	8.4	0.0	5.0
20-03-03	24.5	10.5	40	31	11.7	2.7	2.5	4.0
21-03-03	25.0	10.5	42	34	6.1	11.5	0.0	4.9
22-03-03	26.5	10.5	30	35	5.6	0.1	0.0	5.5
23-03-03	28.0	12.5	42	34	10.1	11.6	0.0	5.4
24-03-03	29.8	18.5	49	35	6.3	11.7	0.0	6.2
25-04-03	31.0	22.0	49	29	7.8	11.5	0.0	5.9
26-04-03	32.0	20.5	38	32	9.8	11.3	0.0	8.7
27-04-03	20.5	17.5	43	33	7.3	4.0	0.1	6.0
28-04-03	27.5	14.0	57	36	8.2	2.0	0.3	4.0
29-04-03	27.0	15.5	48	39	4.5	8.2	0.0	5.2
30-04-03	28.5	17.0	52	34	5.2	11.6	0.0	6.0
01-05-03	29.5	19.0	64	43	5.4	10.0	0.0	6.0
02-05-03	29.0	22.0	50	38	4.1	9.6	0.0	6.4
03-05-03	29.5	19.0	40	34	9.1	0.5	0.0	7.8
04-05-03	25.0	18.0	66	36	12.3	6.0	0.0	4.8
05-05-03	24.0	14.0	77	32	7.1	0.0	0.0	6.0
06-05-03	26.6	14.0	38	17	6.2	10.4	0.0	6.0
07-05-03	28.0	15.0	34	18	5.9	9.4	0.0	7.4
08-05-03	29.0	16.5	33	17	7.5	11.5	0.0	9.4
09-05-03	28.5	17.5	35	20	8.4	11.0	0.0	8.0
10-05-03	28.5	17.0	36	23	6.6	12.0	0.0	8.0
11-05-03	29.0	16.5	31	18	6.4	8.2	0.0	8.0
12-05-03	31.8	17.5	42	21	7.9	5.0	0.0	9.0
13-05-03	32.0	19.0	52	31	6.0	11.0	0.0	7.5

$T_{(Max.)}$: Maximum Temperature
$T_{(Min.)}$: Minimum Temperature
$RH_{(Max.)}$: Maximum Relative Humidity
$RH_{(Min.)}$: Minimum Relative Humidity
WV : Wind Velocity
BSS : Bright Sunshine
RF : Rainfall
Evap. : Evaporation

Appendix II: Daily meteorological data of Palampur for the second wheat crop season (2003-04)

Date	$T_{(Max.)}$ ^{0}C	$T_{(Min.)}$ ^{0}C	$RH_{(Max.)}$ %	$RH_{(Min.)}$ %	WV (Km/hr)	BSS (hr)	RF (mm)	Evap. (mm)
1	2	3	4	5	6	7	8	9
13-11-03	21.5	9.0	57	41	5.3	6.5	0.0	2.7
14-11-03	22.0	11.0	57	58	4.0	5.9	0.0	2.9
15-11-03	21.5	11.0	64	64	4.2	4.8	0.0	2.2
16-11-03	19.8	9.5	65	94	4.5	3.5	0.0	2.0
17-11-03	18.0	6.5	82	89	5.1	0.0	5.0	1.0
18-11-03	15.5	5.5	93	43	5.9	0.2	14.5	1.1
19-11-03	19.5	7.5	65	32	4.2	7.5	11.4	1.9
20-11-03	21.2	6.5	57	38	4.7	8.3	0.0	2.5
21-11-03	21.5	7.8	62	38	4.3	9.8	0.0	2.6
22-11-03	23.3	6.5	57	39	6.6	9.8	0.0	2.7
23-11-03	21.0	6.8	54	43	6.1	9.5	0.0	2.8
24-11-03	21.3	7.0	64	46	3.5	9.5	0.0	2.8
25-11-03	20.5	7.0	65	41	7.8	9.5	0.0	2.8
26-11-03	21.0	7.0	86	39	5.2	9.5	0.0	2.7
27-11-03	21.0	6.0	60	36	5.6	9.4	0.0	2.8
28-11-03	20.0	5.5	62	41	5.0	9.4	0.0	2.5
29-11-03	19.5	6.4	58	36	6.3	9.5	0.0	2.4
30-11-03	20.5	5.5	67	60	4.8	9.4	0.0	2.0
01-12-03	18.5	5.0	70	40	4.2	4.8	0.0	1.3
02-12-03	20.7	7.5	65	45	4.0	8.3	0.0	1.8
03-12-03	20.8	8.8	60	45	5.6	6.8	0.0	1.8
04-12-03	19.5	8.0	67	43	5.4	3.2	0.0	1.3
05-12-03	20.4	7.8	68	47	4.7	5.8	0.0	2.1
06-12-03	21.5	8.0	67	49	5.0	9.3	0.0	2.2
07-12-03	21.5	8.5	61	39	6.0	9.2	0.0	2.2
08-12-03	21.2	8.0	62	42	5.0	9.3	0.0	2.3
09-12-03	21.8	8.5	65	65	4.9	9.0	0.0	2.0
10-12-03	20.2	10.5	61	49	4.5	7.5	4.9	1.8
11-12-03	20.5	9.0	58	52	5.5	8.7	0.0	1.9
12-12-03	20.0	8.5	75	59	6.2	7.5	0.0	2.1
13-12-03	18.5	8.5	66	50	5.9	5.0	4.3	2.3
14-12-03	18.0	8.5	65	50	5.1	1.0	0.0	2.3
15-12-03	21.0	10.0	65	70	8.5	9.0	0.0	2.5
16-12-03	18.0	7.0	75	59	11.2	3.5	11.4	1.0
17-12-03	16.0	6.0	75	56	5.6	8.6	0.0	2.4
18-12-03	17.0	5.8	72	49	5.1	9.0	0.0	1.6
19-12-03	18.0	5.0	76	55	5.5	8.4	0.0	1.4
20-12-03	18.0	6.0	62	41	4.7	9.2	0.0	1.7
21-12-03	18.5	5.8	60	44	5.7	9.2	0.0	2.0
22-12-03	18.5	5.8	86	38	6.2	8.5	0.0	1.9

1	2	3	4	5	6	7	8	9
23-12-03	18.0	6.0	56	48	5.1	9.2	0.0	1.9
24-12-03	16.0	5.0	72	40	5.1	1.0	0.0	1.5
25-12-03	16.5	5.0	60	35	5.4	9.1	0.0	1.6
26-12-03	16.5	3.5	71	35	4.4	5.0	0.0	1.5
27-12-03	15.0	7.0	60	67	5.5	6.5	0.0	1.4
28-12-03	16.4	5.0	62	50	5.8	5.5	0.0	1.3
29-12-03	14.0	3.0	54	39	5.0	8.5	0.0	2.1
30-12-03	16.5	5.0	67	51	5.3	2.0	0.0	1.7
31-12-03	16.5	5.0	74	67	4.5	0.0	0.0	1.2
01-01-04	16.5	5.0	80	61	4.0	0.8	0.0	1.4
02-01-04	15.5	4.5	70	34	3.8	1.9	0.0	1.1
03-01-04	16.0	4.3	60	49	4.1	7.4	0.0	1.7
04-01-04	15.8	5.0	68	49	4.0	8.6	0.0	1.6
05-01-04	15.6	4.0	75	70	3.9	5.2	0.0	1.1
06-01-04	15.0	4.0	66	54	3.8	1.5	0.0	1.1
07-01-04	16.0	4.0	64	39	5.5	8.2	0.0	1.4
08-01-04	17.0	5.0	72	44	4.4	8.7	0.0	2.0
09-01-04	18.0	5.8	70	43	5.7	6.8	0.0	2.2
10-01-04	19.4	6.5	62	42	5.8	9.2	0.0	2.2
11-01-04	18.0	6.5	77	37	5.7	8.4	0.0	1.9
12-01-04	18.5	6.2	76	62	4.8	8.9	0.0	2.0
13-01-04	18.0	9.0	70	54	5.0	4.0	0.0	1.9
14-01-04	18.5	7.0	73	61	4.3	8.0	0.0	1.8
15-01-04	18.5	7.5	72	51	3.8	8.5	0.0	1.9
16-01-04	18.5	7.5	75	45	6.3	9.0	0.0	1.8
17-01-04	21.5	10.0	39	39	6.5	4.2	0.0	1.5
18-01-04	20.0	5.5	78	56	10.6	1.0	22.0	2.0
19-01-04	16.4	5.0	65	51	5.6	9.2	0.0	1.8
20-01-04	16.2	6.0	62	50	5.0	5.3	0.0	1.4
21-01-04	16.0	7.5	80	95	6.3	4.0	0.7	1.3
22-01-04	13.6	5.7	87	62	7.3	0.0	26.5	1.2
23-01-04	15.5	3.6	97	91	5.2	3.0	24.4	1.0
24-01-04	15.0	2.0	84	67	8.4	0.0	66.0	1.1
25-01-04	14.0	2.0	57	66	4.7	5.5	0.0	1.0
26-01-04	14.5	3.0	71	65	4.5	8.5	0.0	1.5
27-01-04	14.2	2.5	55	47	5.2	5.8	0.0	1.5
28-01-04	15.5	4.0	61	68	5.2	9.0	0.0	1.8
29-01-04	15.0	6.0	74	72	4.1	1.5	0.0	1.8
30-01-04	13.5	4.5	89	83	5.2	0.0	22.8	1.0
31-01-04	10.5	2.0	94	92	9.9	0.0	72.5	0.7
01-02-04	8.4	1.8	76	59	4.9	0.0	12.0	0.8
02-02-04	13.5	2.0	70	59	4.5	8.0	0.0	1.4
03-02-04	15.5	2.5	71	47	4.0	9.4	0.0	1.8
04-02-04	16.0	4.0	71	51	5.2	9.2	0.0	1.9
05-02-04	15.5	4.5	55	47	6.1	10.0	0.0	2.0
06-02-04	16.0	4.0	63	48	5.0	9.8	0.0	2.0

1	2	3	4	5	6	7	8	9
07-02-04	16.5	4.0	62	42	5.1	10.0	0.0	2.2
08-02-04	17.0	4.0	59	62	4.5	10.0	0.0	2.0
09-02-04	17.5	3.8	78	51	5.5	10.0	0.6	1.9
10-02-04	17.5	7.2	58	63	7.4	5.4	17.7	1.4
11-02-04	17.5	6.5	57	42	6.2	8.6	0.0	1.0
12-02-04	20.2	8.2	43	41	5.7	9.5	0.0	1.9
13-02-04	20.8	7.5	53	58	5.4	10.0	0.0	2.2
14-02-04	18.6	8.5	68	51	4.8	8.0	0.0	1.8
15-02-04	19.5	8.0	61	45	5.6	8.2	2.1	2.2
16-02-04	20.0	8.3	47	48	6.1	8.5	0.0	1.6
17-02-04	21.0	10.0	63	50	3.8	9.5	0.0	1.6
18-02-04	20.5	10.5	78	58	6.5	6.5	0.0	2.0
19-02-04	20.5	6.0	81	58	2.0	2.0	15.2	2.0
20-02-04	18.8	7.5	49	28	6.1	8.8	0.0	1.8
21-02-04	21.0	8.5	51	34	4.3	10.3	0.0	2.1
22-02-04	21.5	9.5	55	41	5.3	10.3	0.0	2.8
23-02-04	21.5	8.4	49	45	4.5	10.3	0.0	3.0
24-02-04	22.8	9.5	46	40	6.6	10.3	0.0	3.6
25-02-04	23.6	10.9	49	41	4.3	10.4	0.0	3.3
26-02-04	24.2	10.9	39	54	5.4	10.2	0.0	3.8
27-02-04	25.0	10.9	27	42	9.9	10.4	0.0	4.5
28-02-04	24.5	10.0	69	29	9.2	2.0	0.3	3.8
01-03-04	24.5	9.0	46	29	5.6	10.3	0.0	4.1
02-03-04	23.5	9.6	43	37	6.8	10.4	0.0	4.2
03-03-04	23.0	9.5	40	34	6.5	10.4	0.0	4.5
04-03-04	23.5	9.0	47	32	5.7	10.3	0.0	4.2
05-03-04	23.5	10.5	40	26	5.8	10.4	0.0	4.5
06-03-04	23.6	9.7	40	27	6.0	10.2	0.0	4.3
07-03-04	23.5	12.0	42	22	7.3	9.6	0.0	4.4
08-03-04	24.0	13.0	65	59	6.0	10.5	0.0	4.7
09-03-04	23.0	15.0	70	53	4.8	8.0	0.0	4.5
10-03-04	21.5	8.5	49	41	5.5	2.5	0.0	4.0
11-03-04	25.0	8.5	66	54	4.7	9.5	0.0	4.5
12-03-04	25.2	12.5	51	41	6.7	10.0	0.0	4.4
13-03-04	25.0	12.0	55	33	6.8	10.0	0.0	4.2
14-03-04	26.5	12.0	54	45	6.9	10.0	0.0	4.9
15-03-04	26.0	11.5	57	32	5.2	10.0	0.0	4.6
16-03-04	28.0	13.5	50	36	5.0	10.1	0.0	4.7
17-03-04	30.5	16.4	44	31	8.9	10.5	0.0	5.3
18-03-04	30.4	16.8	40	35	5.6	10.3	0.0	4.9
19-03-04	30.5	14.5	34	27	6.7	9.6	0.0	4.5
20-03-04	28.5	14.0	32	23	7.4	9.5	0.0	4.7
21-03-04	28.8	14.0	29	26	5.9	8.0	0.0	4.5
22-03-04	29.5	14.5	34	57	6.7	9.5	0.0	4.5
23-03-04	30.5	14.8	62	44	5.4	9.6	0.0	4.5
24-03-04	28.5	15.5	54	29	5.3	1.0	0.0	4.0

1	2	3	4	5	6	7	8	9
25-03-04	27.0	12.0	47	18	6.6	5.8	0.0	3.8
26-03-04	27.5	12.0	41	36	6.8	9.9	0.0	4.4
27-03-04	26.0	12.5	35	23	5.6	9.5	0.0	4.5
28-03-04	27.0	12.5	37	23	6.0	9.8	0.0	4.9
29-03-04	27.2	13.0	38	23	6.5	10.0	0.0	4.7
30-03-04	27.0	14.0	42	18	6.9	9.9	0.0	4.8
31-03-04	27.0	13.0	40	57	6.7	10.0	0.0	4.8
01-04-04	28.2	14.0	46	34	5.5	10.3	0.0	4.7
02-04-04	26.5	14.5	41	34	5.1	4.0	0.0	4.0
03-04-04	28.5	15.8	33	30	5.5	6.8	0.0	4.6
04-04-04	30.0	15.5	54	36	5.6	9.8	0.0	5.1
05-04-04	30.0	15.8	45	38	5.4	9.9	0.0	5.1
06-04-04	30.0	17.5	35	20	8.6	10.4	0.0	6.7
07-04-04	29.6	18.3	42	31	5.5	5.8	0.0	6.0
08-04-04	30.0	18.0	34	32	7.0	10.0	0.0	7.5
09-04-04	30.5	16.0	49	44	5.2	6.0	0.0	7.0
10-04-04	30.0	14.5	54	46	9.4	5.0	2.1	5.3
11-04-04	30.0	14.5	47	27	5.6	8.0	0.0	5.5
12-04-04	31.0	15.0	44	30	6.6	10.0	0.0	6.0
13-04-04	31.0	16.5	43	52	6.1	10.0	0.0	6.5
14-04-04	31.5	16.5	35	22	5.8	9.0	0.0	6.5
15-04-04	30.8	16.9	32	22	5.8	11.2	0.0	7.3
16-04-04	31.5	16.9	34	57	5.4	10.8	0.0	7.0
17-04-04	32.0	20.0	55	63	6.6	8.5	0.0	7.0
18-04-04	32.5	17.5	50	36	5.4	3.2	0.0	6.7
19-04-04	31.2	18.2	40	26	5.6	7.0	0.0	7.5
20-04-04	33.0	21.8	60	33	5.7	7.7	0.0	7.8
21-04-04	31.0	15.5	39	36	6.3	3.5	0.1	6.0
22-04-04	28.0	16.0	52	45	7.6	3.0	6.0	6.0
23-04-04	25.5	12.0	61	68	7.8	1.2	11.8	3.8
24-04-04	22.5	13.0	47	35	5.3	4.4	1.5	3.4
25-04-04	26.5	15.0	46	46	4.4	11.0	0.0	4.4
26-04-04	27.5	17.5	65	39	4.7	7.0	0.0	5.5
27-04-04	28.0	17.6	69	48	4.8	5.7	0.0	5.1
28-04-04	27.5	13.0	50	49	7.1	3.9	12.1	2.9
29-04-04	24.5	12.8	57	62	6.9	1.5	1.9	3.0
30-04-04	19.0	12.8	75	43	8.3	0.0	23.0	2.6
01-05-04	23.5	9.1	64	52	8.0	1.6	24.5	2.7
02-05-04	23.5	10.0	64	44	6.0	6.2	0.0	3.8
03-05-04	24.5	11.0	53	56	6.6	10.6	0.0	4.6
04-05-04	28.5	13.8	61	44	4.9	9.7	0.0	5.3
05-05-04	28.8	16.0	56	32	4.8	11.2	0.0	5.2