Secrecy: No.

Chinese Academy of Agricultural Sciences Dissertation

Effect of Irrigation Method and Scheduling on Development and Water Utilization in Winter Wheat

PhD. Candidate : Shiva Kumar Jha

Supervisor : Professor Duan Aiwang

Major : Agricultural Water-Soil Engineering

Specialty : Theory and Technology for Crop Effective Water Use

May, 2016

密级: 论文编号:

中国农业科学院

学位论文

灌溉模式对冬小麦生长发育
及水分利用的影响

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申请学位类别：工学博士

专业：农业水土工程

研究方向：作物高效用水理论与技术

培养单位：农田灌溉研究所

中国农业科学院研究生院

提交日期 2016 年 5 月

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论文答辩时间地点	农田灌溉研究所二楼会议室　2016年5月21日

DEDICATED

To

MY BELOVED PARENTS

摘　　要

本文通过 2013-2014 年和 2014-2015 年两年的田间试验，研究了华北平原冬小麦对不同灌水方式与灌溉制度的响应。试验为两因子设计，分别为灌溉方式和灌溉制度，即当土壤含水量分别下降到田间持水量的 50%、60%及 70%时，分别采用喷灌（SI）、地面滴灌（SDI）及地面灌（FI）方式进行灌溉，通过研究不同灌溉方式及灌溉制度对冬小麦地下和地上部生长发育的影响来确定适宜的灌溉方式和灌溉制度。针对这个目标，试验主要关注于土壤水分动态、根系形态发育、根系吸水、土壤温度以及与产量参数相关的作物生理生态和生长发育的变化。最后，基于这些指标的表现对灌溉模式进行评价，确定华北平原冬小麦高效、简便、实用的灌溉方法与灌溉制度。本试验主要研究结论如下：

1. 利用“Hydrous-1D”模型研究了剖面土壤水分的一维运移规律。灌溉及降水对土壤含水量影响较大，灌溉方式及灌溉制度对 0-40cm 土层土壤含水率的影响更大，也决定着冬小麦产量以及地上与地下部分与产量有关参数的高低。剖面土壤含水量随着灌溉方式及灌溉制度的不同而发生相应的变化，其通过改变剖面根系吸水（RWU）而成为控制灌溉需水量的关键因子。三月底到四月中旬以及五月的中上旬，每日的根系吸水量可达到 6-9 mm/day。可以推测，在这一时间段内如果没有足够降雨的话，则需要对冬小麦进行灌溉。土壤 0-20 cm 土层为冬小麦主要的水分吸收层，这一土层根长密度（RLD）较高，可提供 38-40% 的根系吸水量。无论何种灌溉方式，根系吸水量都随着灌溉频率的增加而增大。由于顶层土层根长密度较大，对所有的灌溉制度而言，地面滴灌（SDI）的根系吸水（RWU）要高于喷灌（SI）和地面灌（FI）；但在 60cm 以下的土层中，地面灌模式的根系吸水要高于喷灌和地面滴灌。Es/ET 随着灌水总量的增加而减少，SDI 的 Es/ET 值最低，可能是由于此模式下土壤表面湿润面积最小。

2、从 3 月份至收获期连续测定的土壤温度显示，地表土壤温度呈现显著波动，并且地表滴灌的地表温度波动大于喷灌和地面灌，这导致土壤表面频繁变干并产生了水分胁迫，特别是 50%田间持水量的处理。通过比较相同灌溉方式的不同灌水下限发现，喷灌 50%田持灌水下限处理的地表温度波动幅度比喷灌 70% 田持灌水下限处理的波动幅度高 4.3℃。相似的，通过比较相同灌水下限的不同灌溉方式发现，最大的地表温度波动幅度之差出现在 70%灌水下限的地面灌和地表滴灌之间，为 3.7℃。比较所有处理发现，最大温度波动幅度之差为 5.4℃，出现在地表滴灌灌水下限为 50%田持的处理与地面灌灌水下限为 70%田持的处理之间。深层土壤温度及其波动幅度随深度逐渐降低，从土壤表面到深层土壤形成了较大的温度梯度。

3、通过洗根后扫描，再经过 WinRHIZO (2007d) 软件分析的方法研究了冬小麦生育期的根系形态变化。所有处理的最大的根系深度和其他根系指标均出现在开花期。表层土壤的根长密度表现为 70%灌水下限的地表滴灌在 2014 年明显高于喷灌，而在 2015 年明显高于地面灌；但 60cm 以下土壤的根长密度则以地面灌最高，其次是 50%灌水下限的喷灌处理。地表滴灌较低的供水速率几乎使所有灌溉水保持在 60cm 以上的土层，因此导致根长密度在顶部的高比例分布，并且降低了渗漏量。开花期表层 0-10cm 土壤的最大根长密度为 41.05 cm cm-3，出现在地面滴

灌处理中，其次为 70%灌水下限的喷灌处理（38.29 cm cm-3）。在 90-100cm 土层，50%灌水下限的地面灌处理的根长密度最高(3.52 cm cm-3)。在 2015 年，地面灌的平均根直径大于 50% 灌水下限的地表滴灌。频繁的灌溉处理显著增加了根生物量、根体积和投影面积。

4、为了确定不同灌溉模式的效率，对比分析了冬小麦的产量组成。结果显示，灌溉方式配以适宜的灌溉制度能够显著提高产量组成，并能实现最优产量与灌溉水有效利用间的平衡。产量与需水量结果分析显示，冬小麦产量最高时的灌溉需水量为 180.27 mm（加上降雨量约为 318.17 mm），即灌水定额为 30 mm 的 SDI 或 SI 需要灌水 6 次，灌水定额为 60 mm 的 FI 则需灌水 3 次；而当灌水量为 154.53 mm 时，预计可以获得最高的水分利用效率（WUE）值。这一结果表明，最高 WUE 可通过灌水定额 30 mm 的 SDI 或 FI 灌水 5 次或灌水定额 60 mm 的 SI 灌水 3 次实现。对比不同处理间的籽粒产量发现，SDI 灌水下限为 60% 田持处理的产量最高为 9.53 t ha-1，SDI 灌水下限为 70%田持处理的产量次之，为 9.37 t ha-1，FI 灌水下限为 50%田持处理的产量最低，为 8.26 t ha-1。SDI 灌水下限为 60%田持处理的的 WUE 最高，为 2.08 kg m-3，SI 同一灌水下限处理的 WUE 次之，为 2.05 kg m-3；SI 灌水下限为 50% 田持处理的灌溉水利用率（IWUE）最高，为 9.38 kg m-3，其次为 SDI 同一灌水下限处理的 9.20 kg m-3。结果表明，SDI 在增加作物潜在产量和 WUE 方面表现得更好。为了获得最高产量或最优 WUE，适宜的灌溉制度和灌水方法应该保证灌水量在 154.53-180.27 mm。这表明在 60% 田持时对冬小麦进行灌溉是效益最优的灌溉制度，SDI 是获取潜在籽粒产量和 WUE 最佳的灌水方法。本研究推荐即使在干旱年份也要在 60% 田持时采用 SDI 进行灌溉，而且建议根据当地天气状况设定灌溉时间。

关键词：土壤水分动态，根系吸水，土壤温度，根系形态，籽粒产量，水分利用效率

Abstract

A field experiment was carried out in winter wheat (*Triticum aestivum* L) during two consequent years 2013-2014 and 2014-2015 to study responses of soil and plant under currently practiced main irrigation methods with promising irrigation scheduling in the North China Plain (NCP). In this two factors experiment, sprinkler irrigation (SI), surface drip irrigation (SDI) and flood irrigation (FI) as three irrigation methods were scheduled to irrigate the crop as soon as the soil water content (SWC) decreases to 70%, 60% and 50% of field capacity (FC). Effects of both irrigation method and irrigation scheduling were studied to understand the phenomena occurred above and beneath the soil surface. With this aims the experiment were carried out to keep focus in determining the overall soil water dynamics, root morphological development, root water uptake, soil temperature, crop physiological growth and development along with yield parameters. Finally, the irrigation systems were evaluated on the basis of those studied parameters to determine the efficient, convenient and practical irrigation method and irrigation scheduling for winter wheat water management at NCP. The main results can be concluded as follows:

The profile soil water dynamics for one dimensional movement of water were studied by using simulation model "Hydrous-1D". Soil water content was highly influenced by irrigation water as well as by precipitation and found great variation at 0-40 cm soil layer depending on irrigation method and irrigation scheduling which finally determined the overall grain yield and yield attribute parameters beneath and above soil surface. Profile soil water content, which correspondingly changed with irrigation method and scheduling becomes the key factor in controlling overall irrigation water requirement by shifting the profile root water uptake (RWU). The daily RWU reached 6 to 9 mm/day at the end of March to mid of April and at early to mid of May. This can be hypothesized that winter wheat requires irrigation in this interval if there was no enough rainfall. It has found that top 20 cm soil layer established as main uptake region which supply 38-40% of total RWU where the existent of root length density (RLD) is higher. The uptake has been found increasing with increasing irrigation frequency for all irrigation method. The RWU leads by SDI compared to SI and FI in upper soil profile at all level of irrigation scheduling due to higher root length density (RLD) for SDI than SI and FI whereas, uptake leads in FI in deep soil profile below 60 cm as compared to SI and SDI. The ratio of evaporation (Es) to Evaporation (ET) decreases with increasing irrigation amount and found minimum in SDI because of minimal wetted surface parameter.

Continuously measured soil temperature from March to harvesting shows that the temperature fluctuation occurred significantly on the surface soil and found more in SDI followed by SI. This cause frequent surface drying on the surface soil and create water stressed particularly in the treatment irrigating at 50% of FC. The maximum surface temperature fluctuation in SI at 50% irrigation scheduling treatment (IST) was found 4.3^{o}C more than that in treatments scheduled to irrigate at 70% of FC, while compared different irrigation level within each irrigation method. Similarly, the greatest surface temperature floatation difference of 3.7^{o}C was found between FI and SDI at 70% while comparing different irrigation method under similar irrigation level. The highest range of surface temperature fluctuation in SDI at 50% IST was found 5.4^{o}C higher than that in FI at 70% IST when estimating temperature fluctuation difference among all individual irrigation treatments. The temperature at deeper soil profile was lowered gradually and temperature fluctuation becomes narrower among the treatments, which create a temperature gradient between surface and deeper soil profile.

The root morphologies of winter wheat were studied by washing root method where the scanned roots were analyzed using WinRHIZO Reg. 2007d software throughout its growth period. The maximum root depth and root morphology was found at flowering for all treatment. In both cropping years SDI with 70% irrigation scheduling treatment (IST) produce denser root followed by FI in 2015 and by SI in 2014 in the top soil whereas, root growth lead by FI followed by SI with 50% IST below 60 cm soil profile. Lower irrigation rate in SDI keeps holding almost all irrigation water in upper 60 cm soil profile which causing to shift RLD upward and reduced drainage. The maximum RLD at flowering was found 41.05 cm.cm^{-3} in SDI followed by SI (38.29 cm.cm^{-3}) with 70% IST in top 10 cm soil profile and RLD lead by FI (3.52 cm.cm^{-3}) with 50% IST in 90-100 cm soil profile. The average diameter shown higher in FI (0.303 mm) followed by SDI (0.287 mm) irrigated at 50% of FC in 2015 crop season. More frequent irrigated treatment significantly increases the root biomass and similar trend was found for root volume and for projected area.

The comparative studies on winter wheat yield components were carried out to determine the most efficient irrigation system. It has found that irrigation method with proper irrigation scheduling had potential to increase the yield components significantly and can be made the balance between the optimum yields with efficient utilization of irrigation water. It was estimated that 180.27 mm irrigation water (about 318.17 mm of total water including rainfall) is the optimal requirement to produce highest grain yield which can be achieved by 6 irrigations with 30 mm per irrigation by SDI or SI system or 3 irrigations with 60 mm per irrigation by FI system. On the other hand, water use efficiency

(WUE) has estimated to gain maximum value with the irrigation amount of 154.53 mm. This shows that the maximum WUE can be achieved by irrigating winter wheat 5 times, 30 mm each with SDI or SI system and maximum of 3 times, 60 mm each with FI. While comparing the grain yields of different treatments, it has found that, maximum grain yield of 9.53 t ha^{-1} was received in SDI at 60% followed by 9.37 t ha^{-1} at 70% with same irrigation method and lowest 8.26 t ha^{-1} in FI at 50% of FC. Similarly SDI with 60% IST received maximum WUE of 2.08 kg m^{-3} followed by SI (2.05 kg m^{-3}) with same irrigation level whereas, irrigating at 50% of FC with SI gains maximum irrigation water use efficiency (IWUE) of 9.38 kg m^{-3} followed by SDI (9.20 kg m^{-3}) with same irrigation level. This concluded that SDI performed better to increase potential grain yield with higher WUE. In this way it can be revealed that either to achieve maximum grain yield or optimal WUE, the optimal irrigation scheduling and water application method should be chosen to assure irrigation water between 154.53 mm to 180.27 mm. This referred that irrigating winter wheat at 60% of FC will be most beneficial irrigation scheduling and SDI will be the best option to obtained potential grain yield, WUE and IWUE. This study strongly recommended to irrigate winter wheat with SDI system at 60% of FC even for dry season and suggested to select irrigation scheduling time according to local weather conditions.

Keywords: Soil water dynamic, Root water uptake, Soil temperature, Root morphology, Grain yield, Water use efficiency

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Abbreviation

English Abbr.	English Full Name
ANOVA	Analysis of variance
BD	Bulk density
CA	Conservation agriculture
CAAS	Chinese Academy of Agricultural Science
Cm	Centimeter
C_{obs}	Observed soil water content
C_{si}	Simulated soil water content
CU	Coefficient of uniformity
D	Days
D	Drainage from root zone
DAP	Di-ammonium phosphate
EC	Electrical Conductivity
E_s	Soil evaporation
ET or ET_c	Evapotranspiration
ET_o	Reference evapotranspiration
EU	European Union
FAO	Food and Agricultural Organization
FC	Field capacity
FI	Flood irrigation
FIRI	Farmland Irrigation Research Institute
FWUE	Farm water use efficiency
G	Gram (unit of mass)
GHS	Greenhouse gases
H	Hour
Ha	Hectare
HI	Harvest index
I	Irrigation amount
IST	Irrigation scheduling treatment
IWUE	Irrigation water use efficiency
K	Potassium
K_c	Crop coefficient

Kg	Kilogram
K_s	Hydraulic Conductivity
L	Liter
LAI	Leaf area index
LSD	Least significant difference
M	Meter
Mg	Milligram
Mm	Millimeter
MPa	Mega Pascal
N	Nitrogen
NBSC	National Bureau of Statistics of China
NCP	North China Plain
^{o}C	Degree centigrade (unit of temperature)
P	Phosphorous
P_2O_5	Phosphorus Pentoxide
PA	Roots projected area
Q	Discharge
R	Rainfall
RL	Root length
RLD	Root length density
RMSE	Root mean square error
RWU	Root water uptake
S or ΔS	Change in soil water storage
SA	Root surface area
SDI	Surface drip irrigation
SI	Sprinkler irrigation
SWC	Soil water content
SWD	Soil water depletion
T	Ton (unit of mass)
USDA	United States Department of Agriculture
WI	Winter irrigation
WUE	Water use efficiency
GY	Grain yield

Chapter 1 INTRODUCTION

1.1. Background

Agriculture is vital industry in China, employing over 300 million farmers. China accounting only 10% of world arable land but produces food for 20% of the world population. China begins farming system in about 7500 BC with classical millet agriculture. The primarily agriculture production in China is rice, wheat, maize, potatoes, tomato, sorghum, peanuts, tea, millet, barley, cotton, oilseed and soybeans. The agriculture reforms implemented in 1980s and increased the declined production occurred after Great Leap (1958-60). In the past 60 years, China's agriculture has developed rapidly, where the development of irrigated agriculture has played a very important role in delivering food security (Peng, 2011). Grain output has exceeded 500 million tons, nearly 5 times since 1996 with an irrigation water supply of 320 -340 billion m^3. However, the state has suggested that the country must produce another 50 million tons of grain per annum by the year 2020. China, the world's top producer of wheat, is likely to import 8 million tons of the grain in 2013-14, the highest in nearly two decades, after the domestic harvest was damaged(Reuters, 2013). This suggests an increased water requirement for agriculture.

Water is the source of life. It's the greatest resource of humanity. It not only helps in survival but also helps in making life comfortable and luxurious. Besides various other uses of water, the largest use of water in the world is made for irrigating lands. Scarce water supplies not only affect production itself but have a direct impact on national food security, which depends on our agricultural productivity. The use of water for domestic and industrial purpose has been increased with increasing urbanization and the improvement in the people's living standard. North China is chronically short of water and subject to frequent drought. Cultivated wheat, which was likely introduced in China in the late 6^{th} to early 5^{th} millennium B.C., is the second most important food crop in China.

Winter wheat (*Triticum aestivum*) is strains of wheat that are planted in the autumn to germinate and develop into young plants that remain in the vegetative phase during the winter and resume growth in early spring. The physiological heading is delayed for winter wheat until the plant experiences vernalization, a period of 30 to 60 days of cold winter temperatures 0^o to 5^oC. Winter wheat is usually planted from September to November in the Northern Hemisphere and harvested in the summer or early autumn of the next year.

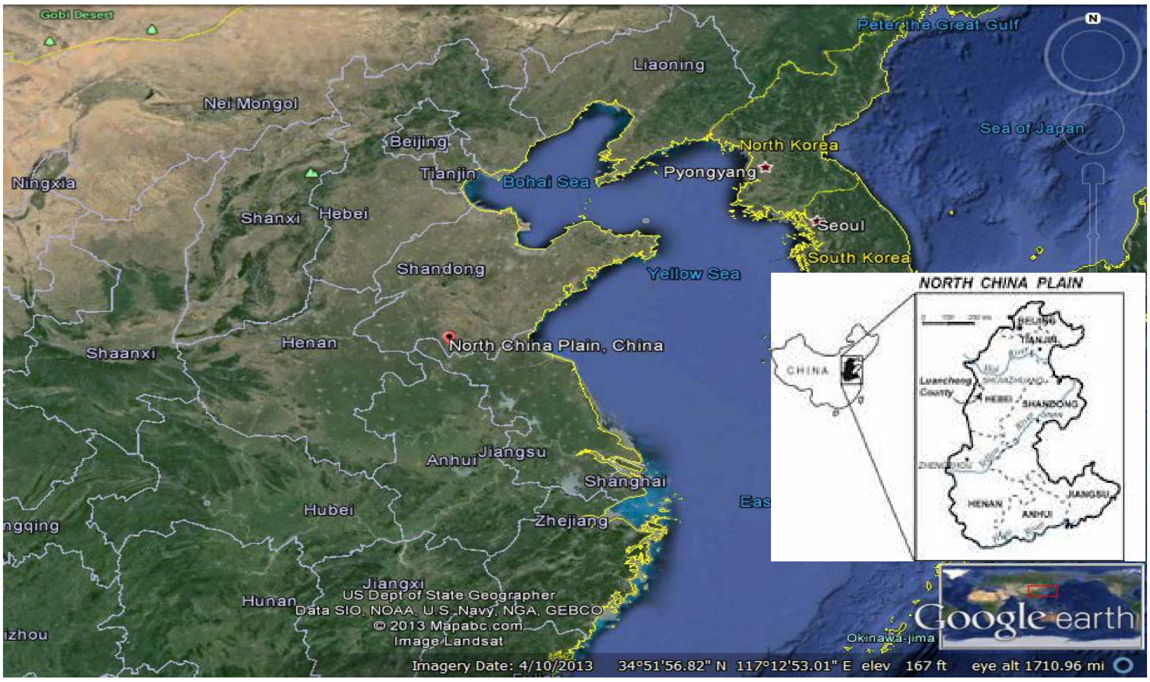


Figure 1.1 North China Plain top views (Source: Google earth)

Geographically, the North China Plain (NCP) refers to the alluvial plain north to the Yellow River, south of the Yan Mountain and east of the Taihang Mountain. The region of the NCP has spanning from 32^{o}N to 40^{o}N and from 114^{o}E to 121^{o}E (Fig 1.1). The total area of NCP is 140000 km^2 with an average population density of 800 people's km^{-2} (Qin et al., 2013). The North China Plain is one of the China's most important social, economic, and agricultural regions. It based on the deposits of the Yellow River and is the largest alluvial plain of eastern Asia. The Yellow River flows through the middle of the plain into Bohai Sea. The North China Plain extends over much of Henan, Hebei, and Shandong provinces and merges with the Yangtze delta in northern Jiangsu and Anhui provinces. The Yellow River meanders over the fertile, densely populated plain emptying into the Bohai Sea. The plain is one of China's most important agricultural regions producing corn, sorghum, winter wheat, vegetables, and cotton. Its nickname is "Land of the Yellow earth". The plain covers an area of about 409500 square kilometers, most of which is less than 50 meters above sea level. Currently, the plain has 17,950 thousand hectare of cultivated land, 71.1% of which is irrigated, consuming more than 70% of the total water supply (Changming et al., 2001). These North China region accounts for more than 45% of the national GDP Although the soil of the North China Plain is fertile, the weather is unpredictable, being the intersection of humid winds from the pacific and dry winds from the interior of the Asian continent. This makes the plain prone to both flood and drought.

1.1.1. Importance of irrigation water management

The crops fade away, resulting lesser crop yield, consequently creating famines and disasters, when sufficient and timely water does not become available to crops. Irrigation can then save us from such disasters. When transpiration rates exceed root water uptake, crop water stress occurs. One of the most important reasons that cause water stress in plants is limited soil water availability. Supplemental irrigation is a way to compensate for soil water loss and to release the water stress of plants when rainfall cannot meet plant water requirements. Crops respond in various ways to soil water deficits and their responses depend upon timing, duration and severity (Hsiao and Bradford, 1983). Whereas, over irrigation may lead to water-logging and may reduce crop yields. Excessive irrigation causes seepage into the ground water of the nitrate that has been applied to the soil as fertilizer. Up to 50% of nitrates applied to the soil can sink in to ground water (Garg, 2007).

In water-saving irrigation techniques generally, the potential to save water will be very prospective (Yuping, 2001). The shallow-wet irrigation for dry farmlands will improve the usage of field water; the sprinkler irrigation and micro irrigation will improve the usage of water at its delivery section and in the field, improve the evapotranspiration environment and reduce evapotranspiration. Replacing winter irrigation (WI) by early or late spring after winter dormancy depending upon soil water content will reduce evaporation and drainage and encourage WUE without any reduction in grain yield (Shao et al., 2011). Irrigation scheduling could reduce the amount of water use to irrigate crops and help to achieve water balance in NCP (Zhang and Wang, 2002). Reducing winter wheat irrigation frequency from four times to three or less during the growth period depending on the weather pattern would greatly reduce supplemental water use (Zhang and Wang, 2002). Further, the drip irrigation (DI) method significantly improved yield and WUE compared with the level-basin irrigation (BI) method under the condition of deficit irrigation (Wang et al., 2012).

Food production in the NCP has been limited because of water scarcity (Liu et al., 2002; Wang et al., 2001; Zhang et al., 2004b) this forces irrigation researchers to improve WUE of winter wheat in order to maintain high-level food production at NCP (Liu and Kang, 2006b; Zhang et al., 2003; Zhang and Wang, 2002). Reducing irrigation frequency and amount can improve irrigation efficiency (Wang et al., 2001) and it is an effective way to reduce water use by placing the wheat under water stress in early growing season (Zhang et al., 2004b). Hao et al. (2014), indicates that WUE may not be the highest when yield was in the high range. Thus an efficient irrigation method and productive irrigation scheduling is required to established for optimum WUE with maximum grain yield.

1.1.2. Irrigation development in China

Irrigation, the artificial application of water to the agriculture soil becomes important in China's traditional agriculture earlier than 2000 B.C. The first canals to divert and wells to lift water for irrigation were constructed 4000 years ago. Since 1949, China engaged in a various water conservancy programme, including the construction of 86,400 reservoirs and numerous pumping stations (53,700 MW total installed capacity) as well as 2 million tube wells (Puli, 1985). The groundwater exploration for irrigation before 1960s was negligible, only small fraction of China's water supply came from groundwater (Wang et al., 2007a). "Dujiangyan" is the oldest and only surviving non-dam irrigation system in the world, and a wonder in the development of Chinese science. It has built over 2,200 years ago in what is now Sichuan province in southwest China, this incredible feat of engineering is still in use today to irrigate over 668,700 hectares of farmland, drain floodwater, and provide water resources for more than 50 cities in the province (Holloway, 2014). By the 1980s irrigation facilities covered nearly half the cultivated land and system installed since the late 1960s extended over a considerable part of north China, especially on the North China Plain (NCP). According to FAO (2015) resource statistic, the total area equipped for irrigation in China has been increasing every year with increasing new irrigation technology and new irrigation practices but the agricultural area actually irrigated has become relatively constant or decreasing after 2006 (Fig 1.2). The irrigated area of 32 province estimated by AQUASTAT (2005) had mention that effective irrigation area (area actually irrigated) was about 16% less than the total area equipped for irrigation.

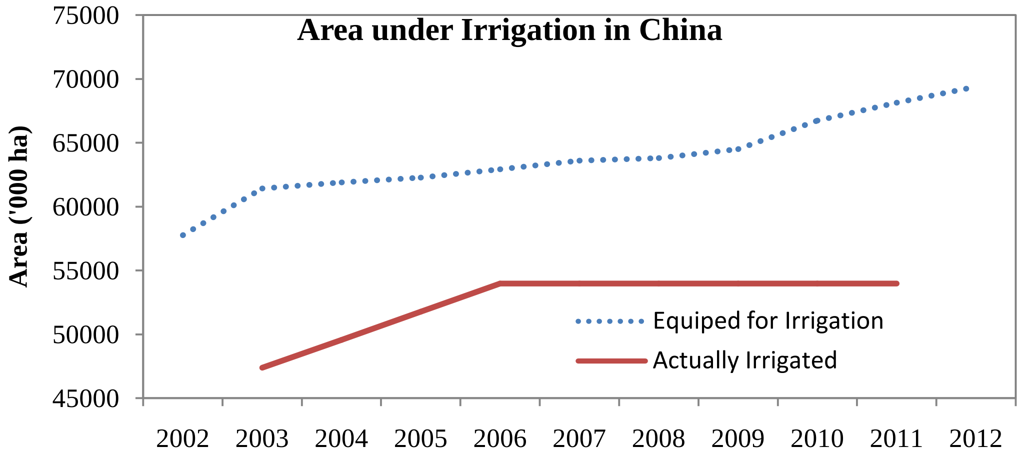


Figure 1.2 Area equipped for irrigation and actual irrigated area in China

After the founding of the People's Republic of China in 1949, the government has carried out large scale construction of water conservancy, guided by the thought that "water conservancy is the life-line of agriculture" (Zezhen and Shangshi, 1987).

1.1.3. Production of irrigated winter wheat in China

China the second largest country by land area is established as second highest global wheat producer and consumer county, whereas winter wheat accounts for about 95% of China's total wheat output (USDA, 2014). By the 20th century wheat had come to occupy about 1/5th of total food grain sown area and ranked second to rice as the most important food grain (Myers, 1978) in world. China's wheat area (24.1 million hectares in 2015-16) ranked third behind India and European Union (EU). However, wheat productivity of 5.4 MT/ha is highest in the world and produce second highest wheat yield 130.2 million tons just behind EU in 2015 (USDA, 2015). The dataset of China's total yearly irrigated wheat production and total irrigated area, recorded by NBSC (2015) are shown in fig 1.3. It shows that the relatively increasing irrigated area plays an important role to achieve increasing yield.

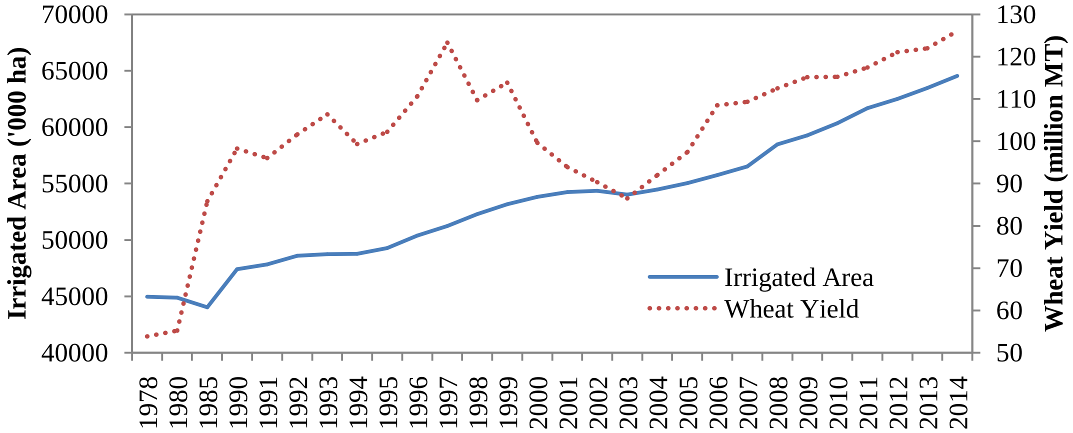


Figure 1.3 Irrigated area of cultivated land and total wheat production in China

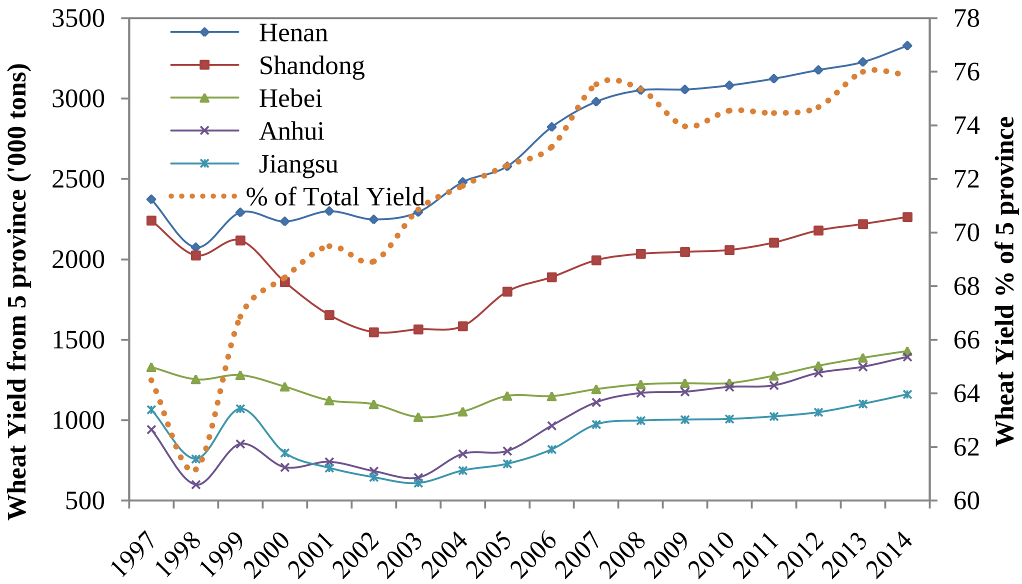


Figure 1.4 Top five individual provincial wheat productions and total yield % of 5 provinces with country total wheat yield(NBSC, 2015)

Henan is one of the top 5 province located in North China Plain along with Shandong, Hebai, Auhui and Jiangsu provinces (Fig 1.4), together contributing more than 75% of the total China wheat production (NBSC, 2015; USDA, 2015)

1.1.4. Upcoming threat in growing winter wheat in China

The urban expansion is associated with a decline in agricultural land use intensity and found that the area of cultivated land per capita is negatively correlated with agricultural land use intensity(Jiang et al., 2013).Total agricultural area under cultivation in fig 1.5 (FAO, 2015) show that the there is no more room to expand cultivation area. Analysts in China report that wheat area is under pressure from urbanization and water shortages. More than 40 percent of China's arable land is suffering from degradation and reducing its capacity to produce food for the world's biggest population (Xinhua, 2014). In the mid-20th century, the advent of diesel and electric motors led to systems that could pump groundwater out of major aquifers faster than drainage basins could refill them. This can lead to permanent loss of aquifer capacity, decreased water quality, ground subsidence, and other problems (FAO, 2004). The future of food production in the areas such as the North China Plain is threatened by those phenomenon's.

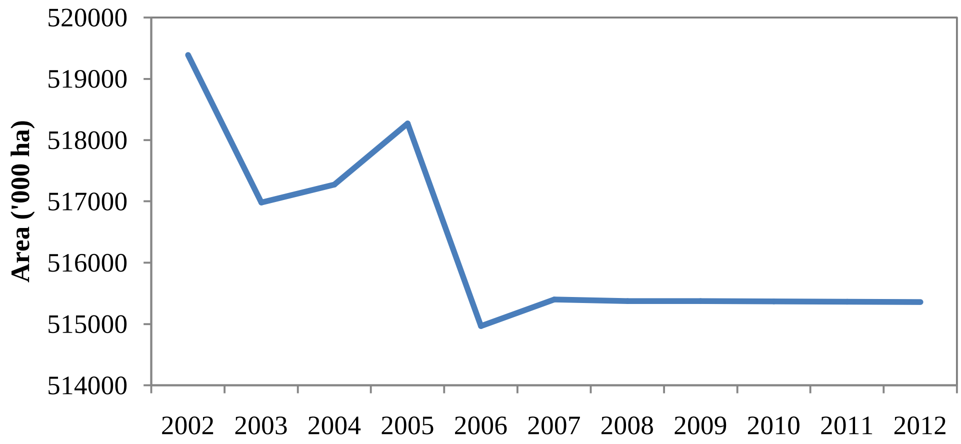


Figure 1.5 Total agriculture area under cultivation in China

China has about 21% of the world population, with about 6% of the world's fresh water and 9% the world's farmlands. The extensive use of groundwater for irrigation agriculture under variable conditions has resulted in the rapid decline of the groundwater table especially in areas north of Yellow River, leading to hydrological imbalance and unsustainable agricultural production (Kendy et al., 2004; Wang et al., 2008a). Yao (2009), had estimated that draught affects an average of 15.3 million ha of farmland every year, nearly 13% of the total farming area. The field experiment carried out with six irrigated crops in different crop rotations by Yang et al. (2015) to examine the drawdown in NCP, has found that water tables are dropping approximately 1 m every year mainly due to water withdraws for irrigating winter wheat. He concluded that winter wheat had the least recharge with 27 mm/year depending upon the amount of irrigation water pumped from the aquifer.Currell et al. (2012), had also mention that the groundwater level declines 0.5 to 3 m/year throughout northern China in the last three to four decades, particularly in the deep aquifers. Li (2006), had estimated that by the end of 2030, the deficit at the national level would be around 13 billion m^3, but at the same time the water shortage in North China Plain would be as high as 25-46 billion m^3. Several other researchers had predicted similar trend for declining groundwater future.

As one of the main constraints of the world's agricultural development, drought has raised great concerns. The impacts of drought had badly influences the production of winter wheat and hunt the food security of China. The drought index projected by Song and Zhao (2012) has shown that the drought maybe the severe in the near future 10-30 years.Lin et al. (2013), has also mentioned that, the global agriculture losses have continuously grown due to increasingly severe droughts in the past three decades. The commodity intelligence report by USDA (2011) had clearly mentioned the providences Henan, Anhui, Shandong, Hebei and Shanxi, as the top 5 contributor of winter wheat (about 2/3rd of China total wheat production) which has been categorized under severe drought region (Fig 1.6). Zhang et al. (2013), found that the weather-driven yield of winter wheat was declining by 10% during the past three decades in NPC. Agricultural sector is responsible for 17-20% of total annual greenhouse gases (GHGs) emission and 62% of the total fresh water used in China (Jinxia et al., 2012). Since the advent of mechanized pumping wells in the 1990s, however, production has increased to two crops winter wheat and maize every year (Kendy et al.,

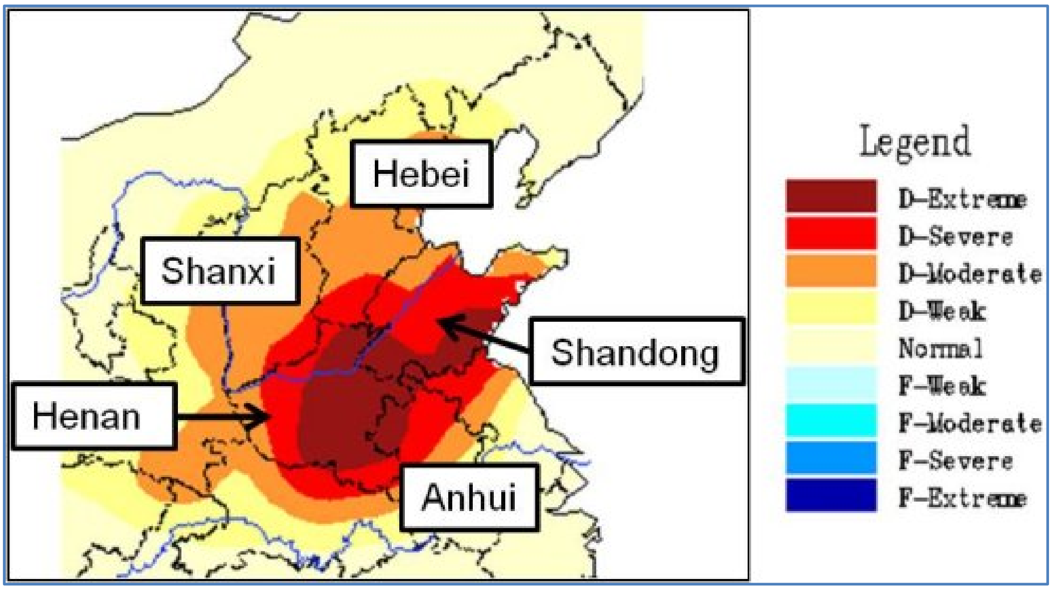


Figure 1.6 China drought index condition monitor in 2011 by USDA

2003). Pumping of water for irrigation is one of the most energy consuming on farm processes which promote GHGs emission and declination trend of groundwater table with minimum fresh water uses.

1.1.5. Weather pattern and source of irrigation water in the NCP

China is located in the south-eastern part of the Asia-European Continent, facing the Pacific Ocean. This geographic location brought about intensive influence of remarkable monsoon characteristics on the climate and the average precipitation decreases from the south-east to north–west. Northern, the north-eastern and north-western parts with arid or semi-arid characteristics, the total annual runoff amounts to 18% of the country's total, but the total cultivated land of these areas amount to 62% of the country total cultivated area (Zezhen and Shangshi, 1987). China's climate is mainly dominated by dry seasons and wet monsoons, which lead to pronounced temperature differences between winter and summer. The climate in the NCP is continental semi-arid with average annual temperature of 12-13^{o}C (Qin et al., 2013).

Rain was the lifeblood of farmers, who likely would have placed special significance on the relationship between an alligator's bellowing and coming of rain. The mean annual precipitation of 1951-1995 was 554 mm as mention by Qin et al. (2013), while the seasonal distribution of precipitation is uneven, with about 75% of its precipitation occurring throughout the summer flood season from July to August. In most parts of the county, precipitation is less in spring and winter causing frequent drought, but abundant in summer and autumn, brings flood and water-logging. Especially in the northern part, precipitation in the flood season amounts to 70-80% of the year's total. There have been 135 flooding years and 140 drought years in the NCP in the last 500 years (Gazetteer, 1998). Li et al. (2005), and Zhang et al. (2003) has also figure out the similar data for seasonal rainfall pattern. Likewise Zhang et al. (2002) says, average rainfall ranges from 60 to 200 mm at NCP during winter wheat growing season from October to May. The precipitation range of 50 mm in dry to 150 mm in wet years has been pointed out by Liu et al. (2002)for winter wheat season at NCP. The rainfall pattern in NCP are variable today, where monthly precipitation in winter had significant increasing trend in most parts, while it showed a decreasing trend from July to September in some parts (Fan et al., 2012). The rainfall data over 60 years average at experimental stations has found 161 mm (about 27.65% of annual rainfall) during the winter wheat growing season (October to May)as shown in fig. 1.7. The remaining 421.2 mm (about 72.35%) out of 582.2 mm annual rainfall occurred from June to September which can't use by winter cropping wheat.

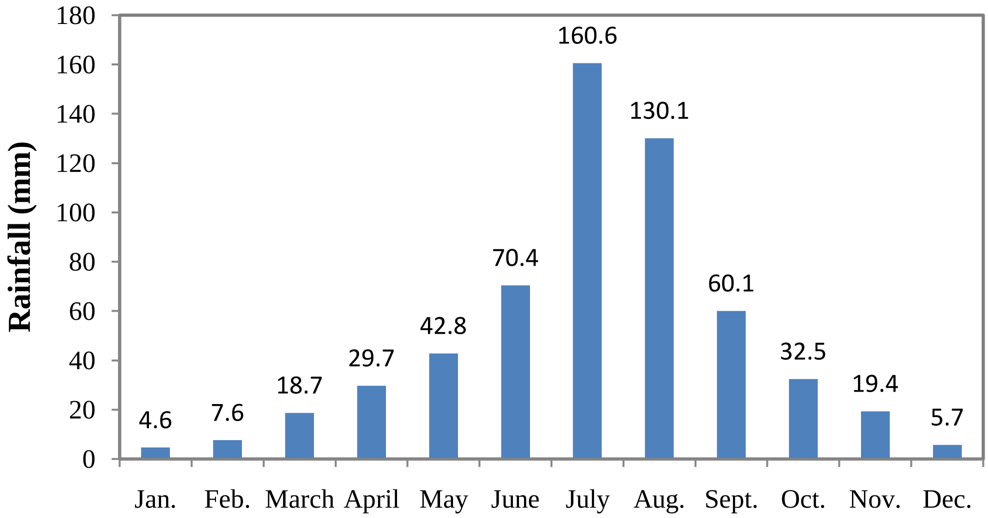


Figure 1.7 Rainfall pattern over 60 years from 1951-2010 at Xinxiang (Source: Xinxiang weather station, Henan)

The North China plain (NCP) lies in the basin of the Huang, Huai, and Hai rivers (3-H Basin) is most important fertile land has only 7.6% of the nation's water resources(Liu et al., 2013b). The North China Plain (NCP) flourishes in the fertile basin of the Yellow River. The NCP aquifer is divided into four main hydro-geological zones from the Taihang Mountains on the west to the Bohai Sea on the east, these zones are based on the geomorphology of paleo channels (Cao et al., 2013).

Although surface water dominated Chain's irrigation development in the 1950s and 1960s, since the end of 1960s groundwater gradually has become the primary source of irrigation water (Lin et al., 2008; Zhang et al., 2008a). Kendy et al. (2003), had also reported that alluvial aquifers underlying the North China Plain constitute the primary source of water for irrigation, as well as for urban and industrial use. The water resource per capita in NCP is 501 m^3, which is only 23% of China's average (Xia et al., 2006). A considerable proportion of irrigation water comes from wells. The official statistics records during 1965-2003, the number of tube wells increased from 0.2 million to 4.7 million. According to statistics, 1103 million ha of arable land are irrigated with water from wells, and the annual exploitation of underground water has reached 40 million m^3 (Mengxiong, 1987). In North China, the output of groundwater reaches to 6.86 million m^3/day which is 87% of the total water consumed.

1.1.6. Water requirement and irrigation technologies used for winter wheat at NCP

Water Consumption and Irrigation Quota:

Yuping (2001), had predicted that the water demand in agriculture in China by 2030 will 640 billion m^3 by 2030. Several researchers (Li et al., 2013; Liu et al., 2002; Wang et al., 2008a; Zhang et al., 2002)had mentioned that the rainfall during the winter wheat growing season is not sufficient to produce optimal grain yield. Supplemental irrigation is thus required because the water consumption for winter wheat is about 430-470 mm (Zhang et al., 2003) much more than the available precipitation. In general, farmers irrigate winter wheat three to five times, with 180-300 mm to meet water consumption of 450-500 mm for each season, from wells, rivers or reservoirs (Zhang et al., 2002). The average water consumption of 453 mm was determined for winter wheat from the five season experiment carried out by Liu et al. (2002) at Luancheng Station in NCP using large-scale weighing lysimeter. The water consumption of winter wheat accounts for more than 50% of the total water consumption at NCP (Li et al., 2008). Sun et al. (2006), has reported that 300 mm of irrigation amount, corresponding to ET value of 426 mm is an optimal for maximum yield in the NCP. The experimental results by Li et al. (2013) has shown that winter wheat irrigated 60 mm each at jointing and heading stages resulted in the highest grain yield and water use efficiency (WUE). With increasing amount of irrigation, the total water consumption increases (Dong et al., 2013). While the soil waters consumption and its ratio to total water consumption decreases significantly. He further concluded that irrigating with 60 mm water each at jointing and anthesis stages would be the optimal water saving and planting modes for the winter wheat production in North China Plain. Similarly, Zhang et al. (2011) concluded that reference evapotranspiration (ET_o) was relatively constant from 1979 to 2009. However, the actual seasonal evapotranspiration (ET) of winter wheat under well watered condition gradually increased from 1980s to 2000s and found mean seasonal ET 401.4 mm, 417.3 mm and 458.6 mm in 1980s, 1990s and 2000s, respectively. Kong et al. (2012), studied the annual water consumption using energy balance approach, and revealed that the average ET and water consumption rate (WCR) of winter wheat growth season were 444.53 mm and 1.81 mm/day respectively. Mo et al. (2005), predicted 330 to 500 mm of ET for irrigated winter wheat condition with SVAT-crop growth model using remote sensing data at NCP.

Irrigation water application method:

As a technical measure, the water-saving irrigation method is employed to make full use of irrigation water resources, improve water usage efficiency, and achieve high yield and efficiency in grain production. By the 2nd century AD, during the Han Dynasty, the

Chinese used china pumps that lifted water from lower elevation to higher elevation. These were powered by manual foot pedal, hydraulic waterwheels, or rotating mechanical wheels pulled by oxen. The water was used for urban residential quarters and palace gardens, but mostly for irrigation of farmland canals and channels in the fields. Modern irrigation methods are efficient enough to supply the entire filed with water, so that each plant has the amount of water it needs, neither too much nor too little. In China, scientists say they've developed a new irrigation methods that's twice as efficient as today's best technology, part of an increasingly urgent effort by researchers around the world to meet the water challenge (Magistad, 2013).

Historically, the surface (furrow, flood, or level basin) irrigation systems often called flood irrigation has been the most common method of irrigating agricultural land and still is in most parts of the world. Magistad (2013), had reported that surface irrigation is king in China. The localized irrigation which distributes water under low pressure through a pipe networks, in pre-determined pattern with small discharge to each plant or adjacent to it has gaining popularity these days. Drip irrigation, spray or micro-sprinkler irrigation and bubbler irrigation belongs to this category of irrigation system. Now a days, micro-irrigation methods, such as surface drip irrigation were adopted in field experiments for food crops in the NCP (Wang et al., 2008b). Drip irrigation is widely known as the most efficient irrigation system that save a lot of water and overcomes the problem of losing water through deep percolation (Bucks and Nakayama, 1986). Sprinkler irrigation, as one of the useful technologies to increase crop production and water use efficiency, has been extensively used in the NCP (Liu and Kang, 2006a, b). In NCP, the sprinkler irrigation has been used as an alternative irrigation and as an advanced irrigation technique for water-saving and fertigation which accurately control irrigation time and water amount (Li and Rao, 2003). Yuping (2001), had mention to realized that over 80% of China's 22 million hm2 of well irrigation area is sprinkling irrigated or equipped with low-pressure water pipes by the middle of 21stcentury. He further illustrated that 80% of main canals 2933 hm2 had reconstructed and field infrastructure are improved additionally with water control measures. According to Liu and Kang (2006a) the area irrigated by sprinkler irrigation increased from 46,000 ha in 1989 to 2,634,000 ha in 2003. Liu et al. (2011b), reported that the area served by sprinkler irrigation has increased from 440×103 ha in 1990 to 2750 × 103 ha in 2005, which is about 50% of the total area served by sprinkler irrigation in China. Liu et al. (2011a), had concluded that sprinkler irrigation method should be recommended as an efficient irrigation method for winter wheat cultivar in NCP. The trickle irrigation and micro sprinkler irrigation has been promoted by the China's central government as water saving irrigation technologies in the major grain producing regions (Xinhua, 2012).

Irrigation Scheduling:

Farmers at NCP generally irrigate winter wheat four times each season (Zhang et al., 2003). As mention by Li et al. (2005), in traditional cultivation systems of high yielding wheat, it was usual to irrigate more than four or five times during wheat growing seasons. Irrigation frequency in drip irrigation scheduling affects soil water regime, water and fertilization use efficiency and crop yield, although the same quantity of water is applied (Hendawy and Hokam, 2007). Wang et al. (2012), had proved that crop water productivity was highest when drip irrigation was used and irrigations were scheduled when soil water was depleted to 60 and 50% of field capacity. Sprinkler irrigation scheduling has been widely studied for winter wheat using soil water balance and meteorological methods (Schneider and Howell, 2001). Proper scheduling of sprinkler irrigation is critical for efficient water management in crop production, particularly under water scarcity conditions (Pereira et al., 2002).

1.1.7. Winter wheat management principles and practices at NCP

China's farmers have long used techniques such as fertilization and irrigation to increase the productivity of their scarce land. Over time, many farming techniques have been modernized. China's winter wheat crop was often planted in October and will harvest in early June of next year. Here are some general management practices reviewed to established the experiment, however this study does not include any other management except irrigation water application method and irrigation scheduling. Besides these two variables all other management practices were kept constants for all treatments.

Tillage practice

Conventional tillage is commonly used practice for double cropping corn and winter wheat system in the NCP (Jin et al., 2009). Numerous studies have demonstrated that no-tillage is useful to decrease agriculture production costs, improve soil structure, increase organic carbon sequestration, reduce soil erosion (Dabney et al., 2004; Holland, 2004) and maintain or increase crop yields (Baumhardt and Jones, 2002; Ehlers et al., 1994) in contrast to these reports, no-tillage was less successful under conditions of high weed infestation (Soane and Ball, 1998) or in heavy clay soils with little or no N fertilization (Rasmussen and Douglas). The total area of Chinese farmland under conservation agriculture (CA) was more than 6.6 ×106 ha in 2012(Zheng et al., 2014), but the ratio of farmland area under CA to total cropland area in China is still lower than those in the U.S. and Canada. The key factor limiting the application of CA in China is the persistent uncertainty about the actual impacts of CA on crop yield (Wang et al., 2007b). Zheng et al. (2014), had reported that CA will most likely increase maize yield but reduce wheat yield.

Crop and fertilizer management

Winter wheat crop management practice varied place to place at NCP from North to East. Sun et al. (2006), reported 150 kg/ha seed rate with a 20 cm row width and before showing applied chemical fertilizer N and P at rate of 130 kg/ha and 160 kg/ha P_2O_5. The seeding density generally maintained after germination has found 500-600 plants/m^2 as reported by Wang et al. (2012) with row to row spacing of 25 cm. Whereas, seeding rates has found adjusted to achieve a density of 300 viable seeds/m^2 maintaining 20 cm row spacing by Zhang et al. (2010). Average NCP farmers has found applying diammonium phosphate (DAP) at 300 kg/ha, Urea at 150 kg/ha and Potassium Chloride at 150 kg/ha before planting as a suitable fertilizer dose with 150 kg/ha of Urea as top-dressed at jointing.

Water management

Winter wheat production in the NCP relies mainly on irrigation because seasonal rainfall only fulfills 25-40% of its total water requirements (Li et al., 2005). Improving irrigation management is an efficient way to eliminate the problems between water supply and demand (Ines et al., 2002; Kang et al., 2004). To develop proper irrigation management practices, it is quite essential to obtain soil water, solute, and crop responses to various management practices (Wang et al., 2015). It has found that more than 70% of irrigation water resources are used for winter wheat at NCP (Li et al., 2005; Lin et al., 2008). Total irrigation area of the region was about 5.9 million hectares in 2006 (Lin et al., 2008) and it has been expanded to about 6.45 million hectares in 2014 (NBSC, 2015). The result described on the basis of MODIS remote sensing data shows that more intensive irrigation can be observed on the southern Hebei Province, the northern and the eastern Henan province (Lin et al., 2008).

Zou et al. (2013), recommended a balance development of channel lining and micro-irrigation for economic feasible water-saving irrigation approach. Wang et al. (2015), considered different irrigation depth and found 244.7 mm optimum irrigation amount at 75% probability of rainfall occurrence. The field experiment results by Zhang et al. (2003) at Luancheng Station in NCP had showed that about 30% of the total evaporation was from the surface evaporation. Such excess surface evaporation loss can be managed by irrigating farmland with suitable water application method, like surface drip instead of surface flood. Irrigating once before winter wheat enters dormancy (simplified as winter irrigation, WI) is still a popular practice in this region. The results showed that with good soil moisture at showing, winter wheat achieved its maximum grain yield with two irrigation in dry seasons and one irrigation in wet seasons, both without WI (Shao et al., 2011).

1.1.8. Government plan and future preparation for winter wheat production

After the establishment of the New China in 1949, the then-Chairman Mao Zedong stated that "water conservancy is the life vein of agricultural production". The China's Ministry of Agriculture, has estimated the possible cultivation of winter wheat at 22.4 million hectares for 2015/2016 cropping season (USDA, 2014). China has set a minimum purchase price for wheat since 2004 in order to stabilize market prices, protect farmer's income, and boost production. Government planners in 1980s emphasized to improve irrigation along with fertilizer and mechanization of agriculture through agricultural modernization program.

The Chinese government is building a $62 billion grandiose engineering "South-North Water Transfer Project" scheme originally conceived by Chairman Mao. The project would divert 44.8 billion cubic meters of water per year from the Yangtze River in southern China to the Yellow River Basin in arid northern China (Wong, 2007). The project is being built in an attempt to curb the over-withdrawal of groundwater and supply more water to industry, cities, and China's breadbasket in the north. The entire project is projected to take 50 years to complete. As said by Xinhua (2014), the agriculture ministry in November 4, 2014 had announced to create 53 million hectares of connected farmland by 2020 that will allow it to withstand drought and floods.

In recent years, the Ministry of Water Resources forwarded an agricultural water management strategy for 'increasing grain yield and water saving' in north-east China, 'limiting groundwater abstraction for saving' in the NCP, 'water-saving with high efficiency' in north-west China, and 'water-saving with drainage reduction' in south China (Du et al., 2015). Under the "Action Plan for Water Pollution and Control," China government calls for improving water consumption efficiency in industry and irrigation(Hewitt, 2012). Over 46,000 reservoirs in China need to be rebuilt or reinforced to ensure that surrounding farmlands and communities are safe from flooding and have enough water for irrigation (Cocks, 2011).

1.2. Research Rationale/ Significance:

Growing more food with less water will be one of the biggest challenges in the coming era of surging population and increasing climate disruption. Environmental considerations suggested that irrigation water supply for Chinese agriculture should be maintained at around 320-340 billion m^3 a year (Peng, 2011). Water shortage has already occurred in Henan Plains because of over pumping of shallow groundwater and hence a series of environmental geological problems such as regional groundwater level decline (Lan and Liu, 2005), land subsidence (Miao, 2010) and ground fissure (Gao, 2008) have emerged in many cities in Henan Plains, such as Anyang, Hebi, Puyang, Xinxiang, Zhengzhou, and Xinyang. Therefore there is an urgent need to improve water resources management in Henan Plains (Shi et al., 2012).

Henan, located at North China Plain is in the top for growing winter wheat. The winter wheat as main irrigation crop generally, called No.1 water consumer for these areas. Water storage is becoming serious as the quickly society developing, and reducing available water for irrigation will be a basic affair in the future. Many research works have indicated that excessive irrigation might not produce greater grain yield or optimum economic benefits (Kang et al., 2002; Sun et al., 2006). In recent years, limited or deficit irrigation method have been well studied and widely practiced for improving crop yield and WUE; however most of these studies have only focused on the effect of irrigation scheduling using a single type of irrigation method (Wang et al., 2012). In addition, studies conducted on irrigation demand management often focus only on irrigation scheduling (Endale and Fipps, 2001) and pay minimal attention to irrigation methods. Thus, a combined approach of irrigation methods and scheduling is required (Pereira et al., 2007). (Shan 2002, Kang 2003) had also mention that, as the water-resource becomes increasingly serous in the NCP, there is a need for adopting water-conserving irrigation methods and optimum irrigation scheduling for food crop irrigation.

Drip irrigation is widely known as the most efficient irrigation system that save a lot of water and overcomes the problem of losing water through deep percolation (Nakayama and Bucks 1986). On the other hand sprinkler irrigation has the potential for improving water use efficiency and grain yields, it is increasingly being used in NCP (Liu and Kang, 2006b). Modern sprinkler packages can be highly efficient in terms of uniformity and application efficiency (Schneider, 2000), as can SDI (Camp, 1998), and numerous studies have documented high crop productivity using either type of system. It is known that due to the water interception by crop canopy during the sprinkler irrigation and low discharge rate in surface drip irrigation with minimum surface wetted perimeter compared with flood irrigation may results entire soil water dynamics and hence change the above as well as below ground surface soil-water-crop interaction. Relatively few studies have been carried out to study the above and below ground soil-water-crop interaction for winter wheat at North China Plain under three irrigation method (Sprinkler irrigation, Surface drip irrigation and Surface flood irrigation) with different irrigation scheduling.

This research study has an attempt in developing the possible combination of three most popular irrigation methods preferred by NCP farmers and three most suitable irrigation scheduling based on several reviewed. The irrigation combinations are evaluated on the basis of crop growth above and beneath the soil surface, the productivity, soil water dynamics, water use efficiency and irrigation water use efficiency. The study conclusion and recommendation will play an important role in solving the issues addressed in the introduction section of each chapters of this thesis. This study will be the helpful tools to maintain groundwater resources nearby Xinxiang City of Henan Plains in some extent. This research study was developed to make more practical and motivate irrigation system for the NCP farmer and will be the references for irrigation researchers in producing optimum winter wheat with minimal irrigation water.

1.3. Research Objective

The main objective of this study was "to co-relate soil and plant response under suitable irrigation practices for producing more winter wheat in the North China Plain". This main objective was supposed to achieve with following specific objectives:

i. To compare three most popular irrigation water application methods with fixed irrigation amount currently practiced by NCP farmers for growing winter wheat.

ii. To identify suitable irrigation scheduling among three most practical irrigation scheduling levels for optimum yield of winter wheat.

iii. To study the phenomena occurred above and beneath the soil surface in applying irrigation water with different irrigation method under different soil water content.

iv. To develop the practical and easily acceptable winter wheat irrigation management tool to save NCP water resource with optimal grain production.

Chapter 2 RESEARCH METHODOLOGY

2.1 Experiment Site Description

A field research was conducted at the experimental station of Farmland Irrigation Research Institute (FIRI), Chinese Academy of Agricultural Science (CAAS), located (35°08′ N, 113°45′ E and 80.16 m Altitude) at Quiliying, Xinxiang City of northern Henan Province in the North China Plain (NCP). The experimental area is famous for intensive agriculture, where winter wheat and summer maize are the most important crops, normally grown in a double crop rotation using irrigation. It falls under warm temperate continental monsoon climatic zone with four distinct seasons where autumn is cool and the spring usually comes early. The experimental site was well facilitated with irrigation systems and an automatic weather station exists very close to the experimental plots. The mean of 60 years (from 1951 to 2010) annual precipitation is 582.2 mm and the seasonal precipitation from October to May is 161 mm (Fig1.7) with annual sunshine of 2255 h and seasonal sunshine is 1427.5 h. The seasonal water consumption of about 450 -500 mm (Sun et al., 2006; Zhang et al., 2002) and mean seasonal air temperature varies 10-12°C with annual frost-free period is between 189 to 240 days (China.org.cn). The groundwater table is about 50-80 m below the surface (Kang et al., 2002). The top view of experimental plot capture from Google Earth is shown in Fig 2.1.

Figure 2.1 Bird view of experiment plot with exact location from Google earth

2.2 Soil Specification

The soil environments such as physical and hydraulic parameters were investigated before the irrigation treatments started and are presented in Table 2.1 for different root zone depths. The average sand (55.21%), silt (40.27%) and clay (4.52%) were investigated by hydrometer analysis (Bouyoucos, 1927)is classified as sandy loam texture using (USDA) Marshalls soil texture triangular diagram. The average bulk density (BD) of 1m deep soil profile determined by core sampling method was found 1.51 g/cm^3 and soil water content (SWC) determined using pressure plate at field capacity (θ_{FC}) as0.3104 cm^3/cm^3, permanent wilting point (θ_r) as0.0313 cm^3/cm^3, saturation capacity (θ_s) as 0.403 cm^3/cm^3 and available soil water were calculated as 0.2791 cm^3/cm^3. The limiting values for field capacity (θ_{FC}) and permanent wilting point (θ_r) were measured in the laboratory as soil water content at a specific suction pressure of 33 and 1,500 kPa (Wang et al., 2012). The hydraulic conductivity (K_s) was determined by using Rosetta Lite v.1.1 software, and has found 51.81 cm/day in an average for 1 m soil profile. The value for K_s has found lower for 20-60 cm soil depth and greater at 80-100 cm because of relatively more clay and excessive sand contain at the top and bottom layer respectively. The average available soil nutrients (Table 2.2); Nitrogen (N), Phosphorous (P), and Potassium (K) of the experiment site were 16.57, 11.53, and 145.65 mg·kg^{-1}, respectively; pH and Electrical Conductivity (EC) of soil were 8.5 and 242.10 μs.cm^{-1} whereas soil organic matter content was investigated as 1.10 g.kg^{-1}.

Table 2.1 Chemical properties of experimental soil determined before tillage

Soil Depth (cm)	Available N (mg.kg^{-1})	Available P (mg.kg^{-1})	Available K (mg.kg^{-1})	Organic Carbon (g.kg^{-1})	pH	EC (μs.cm^{-1})
0-20	44.32	35.46	211.28	1.88	8.43	181.02
20-40	14.33	12.11	134.66	0.95	8.56	192.92
40-60	6.52	2.55	129.35	0.80	8.54	239.23
60-80	9.11	3.51	135.95	1.04	8.50	262.00
80-100	8.58	4.02	117.02	0.86	8.45	335.33
Average	**16.57**	**11.53**	**145.65**	**1.10**	**8.50**	**242.10**

Table 2.2 Experimental soil specification with physical and hydraulic parameters

Soil Depth (cm)	Particle Size Distribution			Texture	B.D. (g/cm^3)	θ_{FC} (cm^3/cm^3)	θ_r (cm^3/cm^3)	θ_s (cm^3/cm^3)	α (1/cm)	n	K_s (cm/day)
	% Clay	% Silt	% Sand								
0-20	3.80	43.14	53.06	Sandy Loam	1.56	0.3408	0.0302	0.4087	0.016	1.4629	55.85
20-40	6.61	45.43	47.96	Loam	1.58	0.3076	0.0362	0.4033	0.011	1.5089	39.79
40-60	6.06	48.33	45.61	Sandy Loam	1.54	0.3269	0.0358	0.4086	0.009	1.5402	43.98
60-80	4.55	47.49	47.96	Sandy Loam	1.42	0.2831	0.0325	0.412	0.011	1.5161	52.57
80-100	1.57	16.95	81.48	loamy Sand	1.45	0.2937	0.0340	0.3931	0.047	1.8359	131.2
Average	4.52	40.27	55.21	Sandy Loam	1.51	0.3104	0.0313	0.403	0.019	1.4435	51.81

2.3 Tillage and Seeding

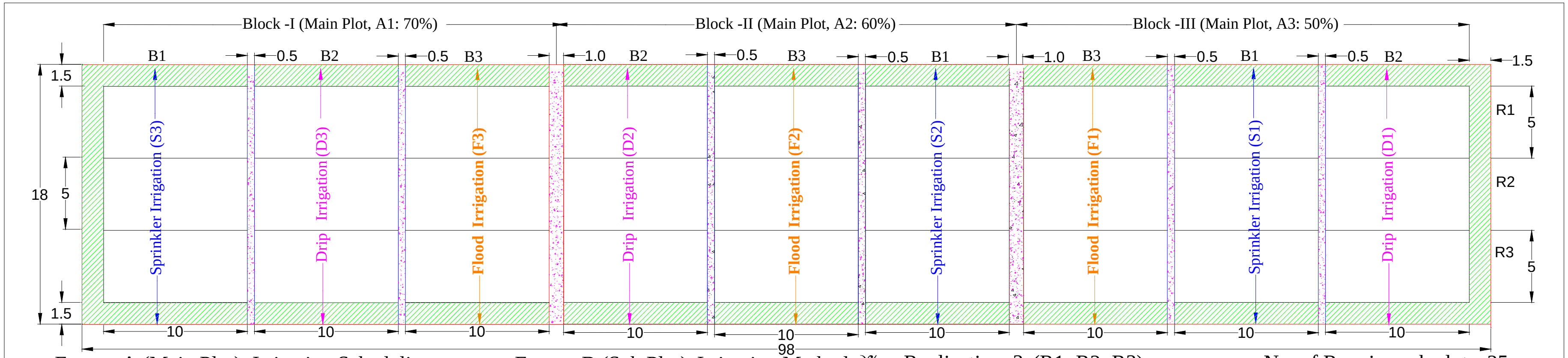
Seed beds were prepared by tractor drawn rotary cultivator, plowing 20 cm deep and bigger soil clods were smoothen by harrow to make completely leveled flat bed. The equal fertilizer basal dose is as: N: 120 kg/ha (50% of total N) as ammonium nitrate, P: 90 kg/ha as calcium superphosphate, and K: 30 kg/ha as potassium sulfate (Gao et al., 2014) has been received by all treatments. The application of remaining 50% N: 120 kg/ha as ammonium nitrate was carried out by hand broadcasting for sprinkler and surface flooding just before first irrigation where as in drip irrigation it dissolved with first irrigation as top dressing. High yielding winter wheat (*Triticum aestivum* L.) cultivars “Aikang 58” was sown at 180 kg/ha with maintaining 20 cm row to row spacing by tractor drawn seed cum fertilizer drill on 20th October, 2013 and 18th October, 2014 for two cropping seasons.

2.4 Experiment Design

2.4.1. Field layout

The experimental plots were selected nearby the automatic weather station closer to irrigation water source for easy assessable in connecting irrigation systems. The variation of soil physical and chemical properties in vertical soil profile within treatments plots was considerable (Table 2.1 and Table 2.2) and supposed to be constant with average values. The total length of 98 m and width of 18 m was separated from the experimental farm land (Fig 2.1 and Fig 2.2) of GSCAAS. The width of 15 m in middle part of 18 m were split in three longitudinal section with 5 m width each representing 3 replications and 1.5m width around the treatment plots as shown in fig 2.3 was kept as the border area so that to protect the treatments form other cultivated area of farm land. The detail experimental design of the experiment plots is shown in fig 2.3. Two factors split plot design has been determined for this experiment, where irrigation scheduling was considered as the main factor and the irrigation water application method as the sub-factors. Thus, irrigation scheduling at 70%, 60% and 50% are arranged in main pots A1, A2 and A3 respectively. Whereas, irrigation water application methods sprinkler irrigation (SI), surface drip irrigation (SDI) and surface flood irrigation (FI) were arranged in sub plots B1, B2 and B3 respectively. The subplots B1, B2 and B3 are randomly selected within each main block A1, A2 and A3. Each main plot containing 3 sub plots were separated by 1 m borders whereas the subplots were 0.5 m apart within the main plots. The size of each sub pots was 10×15 m^2 which was further divided in 3 replications as equal plot size of 10×5 m^{2}each and randomized within individual subplots. Since row to row crop spacing was 20 cm (section 2.3), the total crop rows in each plots was 25 and each row of 10 m long.

Figure 2.2 Separated experimental plot from farmland of GSCAAS



Factor -A (Main Plot): Irrigation Scheduling
1. Irrigate at S.M. reaches to 70% of F.C.
2. Irrigate at S.M. reaches to 60% of F.C.
3. Irrigate at S.M. reaches to 50% of F.C.

Design: Split Plot Design (Two Factor)

Factor -B (Sub Plot): Irrigation Method
1. Sprinkler Irrigation (SI)
2. Drip Irrigation (DI)
3. Flood Irrigation (FI)

- Replication: 3 (R1: R2: R3)
- Plots size: 5m x 10m
- Border around : 1.5 m
- Spacing between main plots: 1 m
- Spacing between subplots: 0.5 m

No. of Row in each plots: 25
Row to Row Spacing: 20 cm
Variety: Winter Wheat Aikang 58
GSCAAS: **FIRI**

Figure 2.3 Field experimental design layout and treatment arrangement

2.4.2. Irrigation treatment design

Two factorial irrigation treatments were arranged in split plot design as explained in section 2.4.1. Main plots include three irrigation scheduling (i.e. irrigate as soon as soil water content decreases to 50%, 60% or 70% of field capacity) as one factor and sub plots included three irrigation method i.e. sprinkler irrigation (SI), surface drip irrigation (SDI), and surface flood irrigation (FI) as another factor. Irrigation treatments were coded as:

S_1 = Irrigate with sprinkler as soon as soil moisture decreases to 50% of FC

S_2 = Irrigate with sprinkler as soon as soil moisture decreases to 60% of FC

S_3 = Irrigate with sprinkler as soon as soil moisture decreases to 70% of FC

D_1 = Irrigate with surface drip as soon as soil moisture decreases to 50% of FC

D_2 = Irrigate with surface drip as soon as soil moisture decreases to 60% of FC

D_3 = Irrigate with surface drip as soon as soil moisture decreases to 70% of FC

F_1 = Irrigate with surface flooding as soon as soil moisture decreases to 50% of FC

F_2 = Irrigate with surface flooding as soon as soil moisture decreases to 60% of FC

F_3 = Irrigate with surface flooding as soon as soil moisture decreases to 70% of FC

2.4.3. Irrigation treatment management

The NCP farmers generally irrigate their winter wheat in early or late spring after winter dormancy depending on soil moisture condition. Several researchers mention that the best time to irrigate winter wheat is after its dormancy period when crop turn green (Xia et al., 2006). Irrigating winter wheat after it turn green do not reduce grain yield and significantly increase WUE (Shao et al., 2011). Considering such references as a preliminary concept, the experiment was designed to conduct irrigation treatment after crop turn green (mid of March) to harvest (end of May or early June). The first irrigation for all treatments was carried out at the same date (Gao et al., 2014; Zhang et al., 2002) on 18 March, 2014 and 20 March, 2015 for both cropping season. The other successive irrigation scheduling determined on the basis of SWC according to the treatment design as explained above are shown in table 2.3 includes total irrigation amount for all treatments. The precise water meters were connected to individual subplot to apply pre-determined and calculated amount of irrigation water in each plots. The amount of irrigation water during each irrigation scheduling for sprinkler and drip irrigation were set as 30 mm, whereas, 60 mm for surface flood irrigation (Li et al., 2010). The irrigation treatments continuously changing the soil water content during the irrigation period are shown in fig 2.4.

Table 2.3 Irrigation scheduling and amount for treatments in both cropping season

Year	Irrigation	S1	S2	S3	D1	D2	D3	F1	F2	F3
2013-14	Schedule	2014/3/13; 3/28; 4/4; 4/28	3/13; 3/21; 3/28; 4/4; 4/22; 5/4	3/13; 3/15; 3/21; 3/28; 4/4; 4/22; 5/4; 5/16	2014/3/13; 3/25; 4/1; 4/28	3/13; 3/19; 4/1; 4/7; 4/29; 5/16	3/13; 3/15; 3/20; 3/28; 4/4; 4/28; 5/16	3/13; 4/7; 5/6	3/13; 3/28; 4/9; 5/15	3/13; 3/17; 4/1; 4/29; 5/15
	Ammount (mm)	120	180	240	120	180	210	180	240	300
2014-15	Schedule	2015/3/18; 4/17; 5/15	3/18; 3/26; 4/16; 4/29; 5/21	3/18; 3/20; 3/24; 4/16; 4/28; 5/13; 5/21	2015/3/18; 4/23; 5/15	3/18; 3/27; 4/17; 4/28; 5/20	3/18; 3/20; 3/27; 4/14; 4/24; 5/15	3/18; 4/17	3/18; 4/16; 5/19	3/18; 3/23; 4/20; 5/20
	Ammount (mm)	90	150	210	90	150	180	120	180	240

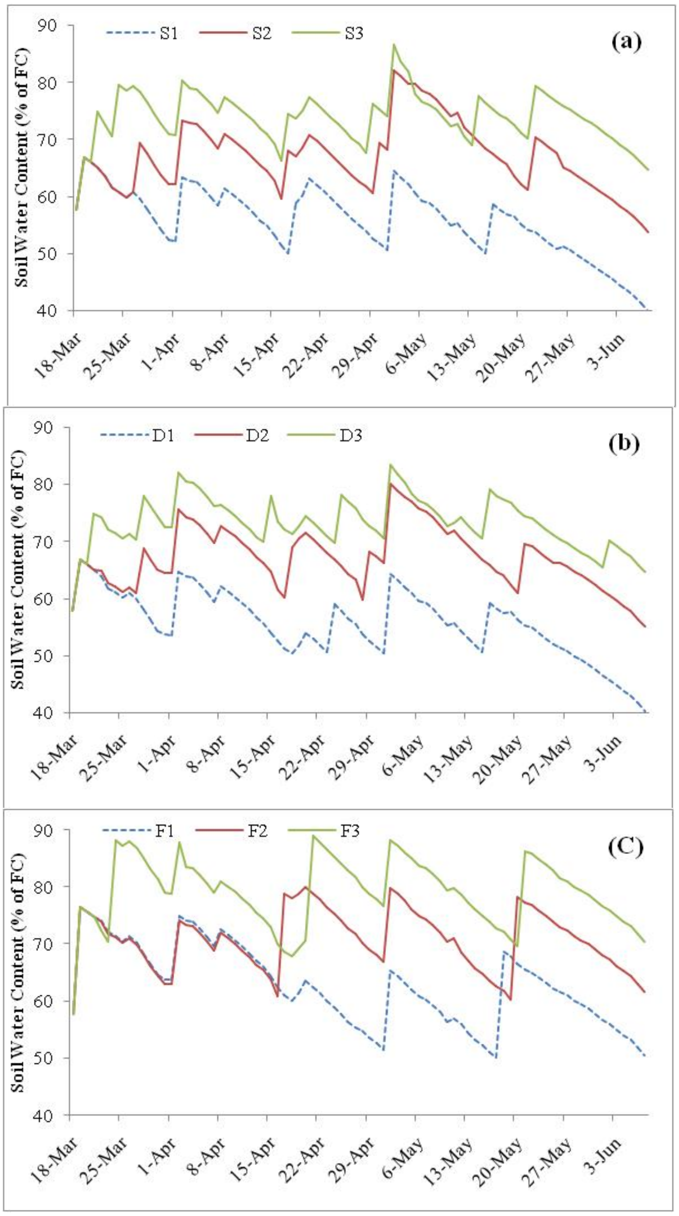


Figure 2.4 Soil water content (SWC) management in SI (a), SDI (b) and FI (c) treatments

2.4.4. Irrigation system design

As explained above each main plot includes three irrigation methods considered as sub-plot and their position was randomized within the main block as shown in fig 2.3. The main line pipe (ϕ = 63 mm) connected to the source of irrigation water with quick connector facilitated with regulating valve, water filter and pressure gauge. The main line runs along the length (98 m) of the experiment plot. The irrigation water diverted to each subplot from main pipe line by sub pipe line fitted with individual water regulating valve, water meter and pressure gauge (Fig 2.7, 2.8 and 2.9). The complete design of irrigation system components is described in the following section. Top view of irrigation system layout in first block is shown in fig 2.5.

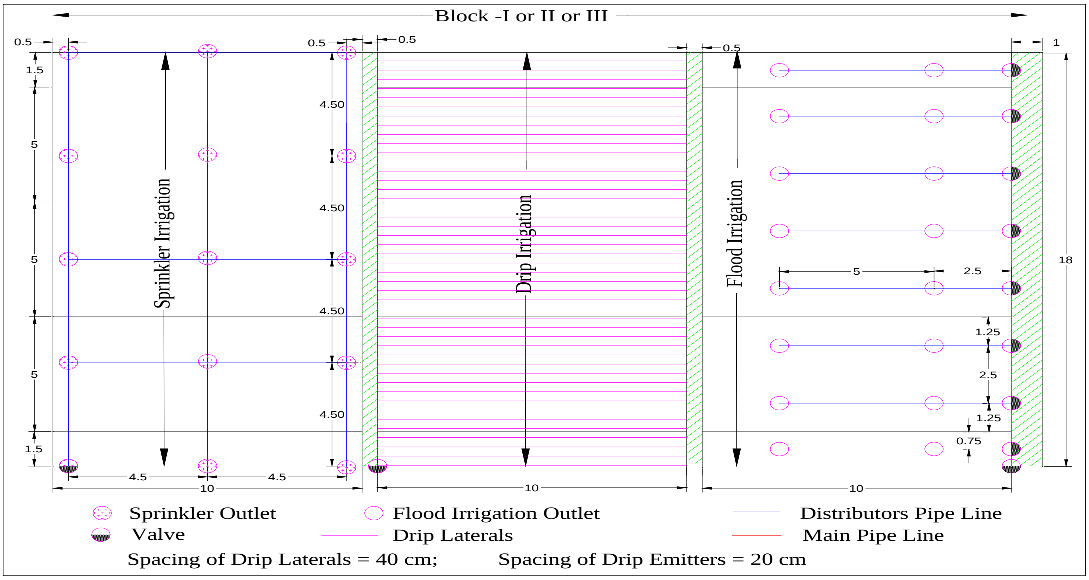


Figure 2.5 Top view of three irrigation systems layout for block-I

<u>Sprinkler irrigation (SI)</u>

The basic parameters of sprinkler used for sprinkler irrigation treatments were as: working pressure 0.2 ~ 0.25 MPa, coefficient of uniformity (CU) about 90% (computed using Christiansen method) under low wind conditions (less than 2 m/s), and sprinkling at 4.5 m radius mounted on 120 cm high risers(ϕ32 mm). In each sprinkler irrigation subplot, at each four corners, sprinklers were sprinkling at 90^o (Q = 0.22 m^3/h), 8 sprinklers sprinkling at 180^o (Q = 0.3 m^3/h) at outer edge, and 3 sprinklers sprinkling at 360^o (Q = 0.55 m^3/h) inside. Sub-main pipe line (ϕ50 mm) consists of water regulating valve, water meter and pressure gauge, divert irrigation water from main pipe line and supply it to connected distributaries pipe line (ϕ32 mm). Design of irrigation water sprinkling coverage is shown in fig 2.6 and sprinkler irrigation in operation with all components is as in fig 2.7.

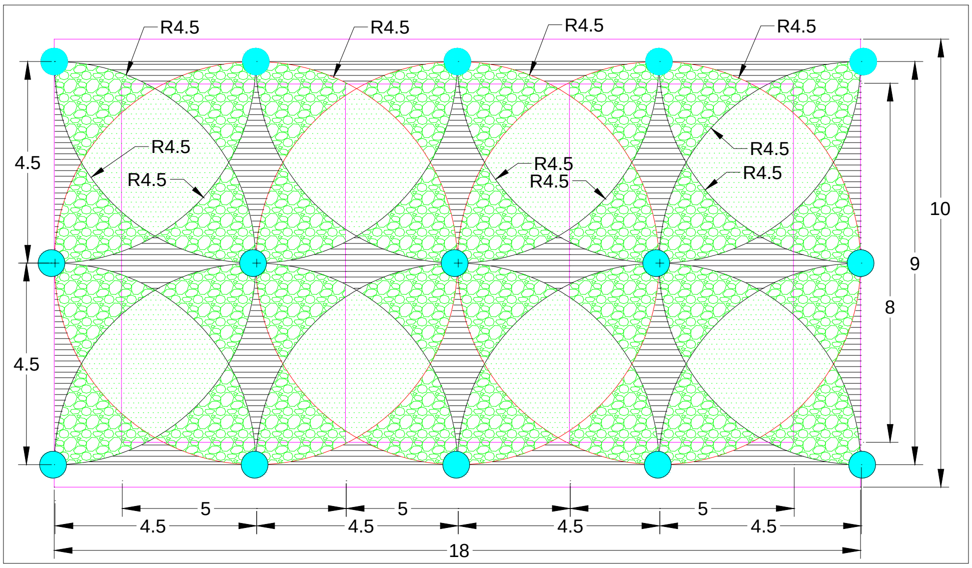


Figure 2.6 Design for irrigation CU and water sprinkling coverage area in SI system

Figure 2.7 Sprinkler irrigation system in operation connected with all components

Surface drip irrigation (SDI)

The surface drip laterals (10 m long, ϕ 16 mm) working at pressure of 0.1~0.15 MPa (Noreldin et al., 2015; Wang et al., 2012) were maintained 40 cm spacing (Fig 2.5) i.e. placed between two alternatively crop rows having inline type emitters (Q= 2.2 L/h) placed at 20 cm apart within each lateral. The sub main line pipe (ϕ32 mm) for SDI consists of same accessories as in SI with some additional components, water filter, fertilizer regulating valve and fertilizer tank connected with thin clear pipe as shown in fig 2.8. Sub line supply fertilizer dissolved in fertilizer tank along with irrigation water to lateral.

Figure 2.8 Surface drip irrigation system in operation connected with all components

Surface flood irrigation (FI)

The surface flooding was carried out by PVC laterals (ϕ50 mm) facilitate with outlets (ϕ50/90 mm; Q=8m^3/h) facing upward. Two laterals of the length 7.5 m and 2.5 m were connected to the sub-main line pipe (ϕ50 mm) at 1.25 m from the both ridge in each replication (Fig 2.5). Thus, for one replication four distributaries outlets (two at 1/3rdand two at 2/3rd from the sub line) irrigate at time to make homogeneous flooding. All distributaries were facilitated with individual flow regulating valve, whereas the water meter and pressure gauge along with main flow cutoff valve were provided in sub-main pipe line. The detail component of surface flood irrigation system is shown in fig 2.9.

Figure 2.9 Surface flood irrigation in operation connected with all components

2.5 Installation of Measurement Tools and Markers

After development of crown root about 3 ~ 4 weeks after seeding, some measurement tools and marker were fixed at unbiased locations with homogeneity. Completing the installation in all the treatments before the crop goes into dormancy will benefit for crop to get enough time to recover till crop become re-green. The markers were fixed the location and then tied each other by colored plastic thread for easy visibility while taking repetitive measurements also protect from further damaging the sample crops as shown in fig 2.10.

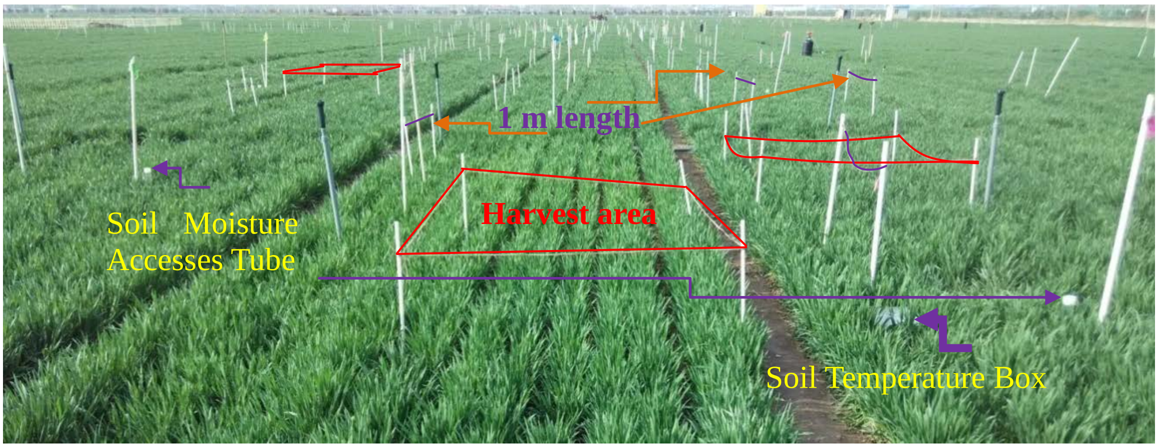


Figure 2.10 Tools and markers installed in the experiment plots for measurements

2.6 Crop Management

All the crop management practices were followed as regular farmer of NCP and make similar management in all the treatments without any biasness. The weeding was done manually throughout the crop growth period after re-green stage to make sure, that there was no growth competition between weeds and winter wheat in any treatment. To protect from uncertain wheat diesis and pest attack, some pesticides at the rate of were spread at full flowering stage with power sprayers as NCP farmers usually applied for winter wheat. After seeding to about one week full germination, and the wheat at maturity was especially cared against birds picking and damaging crops.

2.7 Statistical Analysis and Evaluation

Analysis of variance (ANOVA) for “Two Factorial Split Plot Design” analysis in Microsoft Excel was used to test the effects of irrigation method and irrigation scheduling on yield and yield attributing parameters above and beneath the soil surface. The statistical significance of the differences between two means was determined by least significant difference (LSD) at 5% of significance level ($\alpha = 0.05$). The graphics and data tabulation of the outputs results were carried out on Microsoft Excel and the simulated results were graphics by corresponding models used for the simulation as mention in respective chapter.

Chapter 3 SOIL WATER DYNAMICS

3.1 Introduction

The crop water management practices without knowing the soil water dynamics and water uptake by crop is impossible to support an efficient winter wheat production system. The ratio of air to water stored in the pores changes as water is added to or lost from the soil. Water is added by rainfall or irrigation and is lost through surface runoff, evaporation, transpiration and either percolation or drainage (Evans and Sneed, 1996). Al-Qinna and Abu-Awwad (1998), studied the effects irrigation methods, application rates and initial moisture content on soil water storage and surface runoff. He found that decreasing the application rate from 28.4 to 6.2 mm/h increased soil water storage significantly in all 15 cm layers to a depth of 60 cm.

Field water consumption is the sum of transpiration and soil evaporation between plants also called field evapotranspiration in a single word. It is one of the most difficult water balance elements to determine because of the threefold influence of biology, soil and weather. Chen et al. (2014), has found that evapotranspiration, soil water depletion, drainage and water use efficiency were affected both by weather conditions and irrigation. He further illustrated that irrigating winter wheat once or twice will significantly reduce percolation.Ju et al. (2010), found that elevated atmospheric temperature changed the water distribution and storage in the root-zone soil profile. Liu and Lin (2004), reported that in NCP, when the temperature increased 1-4^{o}C in the growing season of winter wheat, the water requirement was increased by 11.8-153.0 mm. several such research shows that there is many factors along with irrigation system which influences the soil water dynamics.

Zhang et al. (2004a), showed that winter wheat has a profile root system with an average maximum rooting depth of 2 m and most of the root system is concentrated in the upper 40 cm of soil. This is why the roots in the top layer of soil play an important role in soil water uptake. Maximum root growth in the subsoil significantly improved soil water supply to the crop by shifting root growth downward during the growing period due to water depletion in surface soils (Torreano and Morris, 1998). Soil temperature profile distribution (*described in chapter-4*) is greatly affected by irrigation method and undoubtedly influences root water uptake directly or indirectly (Lv et al., 2013a).

Irrigation scheduling is simply known as when to irrigate and how much irrigation water apply. One of the common methods that commonly used to determine when to irrigate is to follow soil moisture depletion (Martin, 2001). An effective irrigation scheduling helps to maximize profit when minimizing water and energy use. Coelho and Or (1999), emphasized that for irrigation scheduling, it is necessary to consider the effect of root water uptake (RWU) rate on soil water dynamics. Lv et al. (2010), concluded that irrigation method influences the winter wheat profile root water uptake even for same irrigation schedule. He also concluded that the root water uptake in the upper zone soil profile increases by raising irrigation frequency. An experiment performed by Camposeo and Rubino (2003) on autumn-shown sugar beet has clearly illustrated that the applied irrigation frequencies significantly affect the root water uptake.

Two major sources of soil water loss, particularly from surface supplies and surface systems, are evaporation and seepage. Various techniques have been tried to reduce losses of irrigation water. Seasonal evapotranspiration (ET) was lowered by 4% ~ 23%, water use efficiency becomes higher by 18% ~ 57% and irrigation water use efficiency was increased by 21% ~ 81% in the sprinkler irrigated field as compared to surface flooded field (Liu et al., 2011a). Kharrou et al. (2011), had demonstrated that drip irrigation applied to wheat in Morocco was more efficient with 20% of water saving in comparison with flood irrigation. However, there are numerous such fractional studies on irrigation method and irrigation frequencies for root water uptake, evapotranspiration, and soil water content, but the convincing complete farmer’s field based water management practices to understand overall soil water dynamics and its influencing parameters is still limited. Thus, the objectives of this field based winter wheat experiment with promoting irrigation method and feasible irrigation scheduling were to estimate soil water dynamics in root zone under surface drip irrigation (SDI), sprinkler irrigation (SI) and surface flood irrigation (FI) with irrigation scheduling at 50%, 60% and 70% of FC which will provide references for further researcher and farmers of NCP in designing a practical and environment friendly irrigation system by selecting appropriate irrigation method with proper irrigation scheduling.

3.2 Principle Measurements

3.2.1 Weather Data

The daily weather data, atmospheric temperature (maximum and minimum), sunshine hour, wind speed, relative humidity, and precipitation were collected everyday at 8:00 AM from the automatic weather station (Fig 3.1) located very near to experimental area. The weather data were taken at 2 m height from the surface as described in “FAO Irrigation and Drainage Paper 56”, (Allen et al., 1998).

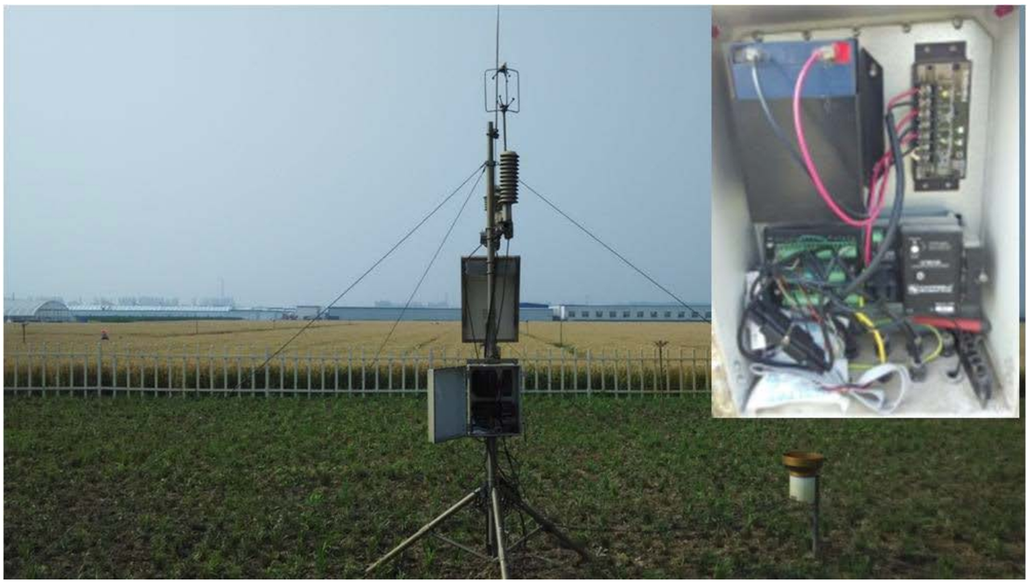


Figure 3.1 Automatic weather station located at the experimental field

3.2.2 Soil water content

Soil water content (SWC) was determined weekly using TRIME (IMKO, Ettlingen, Germany) up to the depth of 100 cm with an interval of 20 cm deep soil layer. Three number of TRIME accesses tube each for one replication in either subplot (i.e. 3 × 9 = 27 nos.) were installed before the irrigation treatment started (Fig 3.2). The SWC of top 0-20 cm soil layer were determined by gravimetric method. Some additional SWC measurement was carried out before and after irrigation and heavy rainfall.

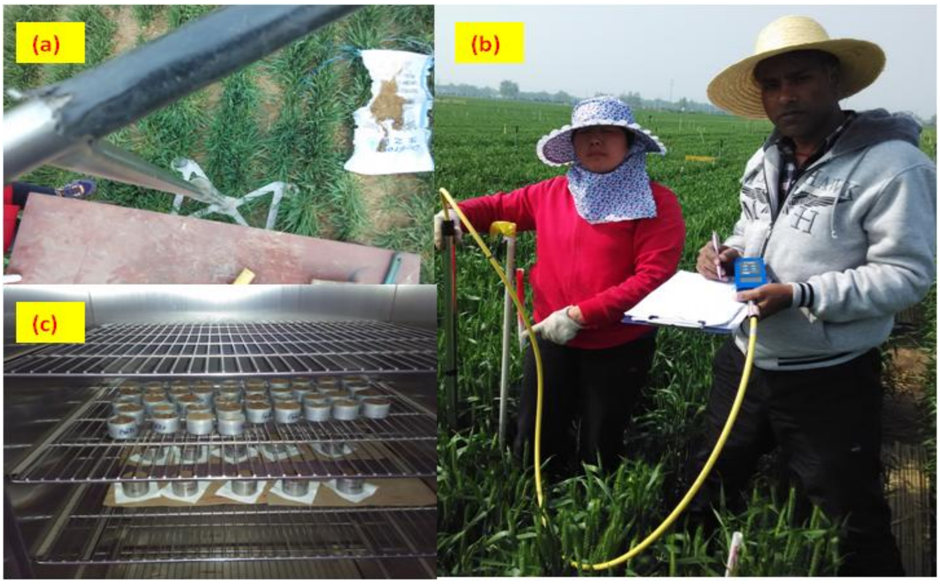


Figure 3.2 TRIME accesses tube installation (a), Soil water content measurement using TRIME (b), SWC measurement by Gravimetric method (c)

The intermediate daily SWC was estimated by using following equations;

i. "FAO Irrigation and drainage paper 56" procedure was followed to calculate the daily actual crop evapotranspiration (Allen et al., 1998) using

$$ET_c = K_c \times ET_o \quad (3.1)$$

Where, K_c is the crop coefficient and ET_o is the reference evapotranspiration.

ii. The crop coefficient (Kc) relationship developed by Gao et al. (2009) was used to determine the daily crop coefficient throughout the experiment period.

iii. Daily ET_o was calculated based on the daily weather data collected according to the Penman-Monteith equation as recommended by Allen et al. (1998):

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (\rho_s - \rho_a)}{\Delta + \gamma(1 + 0.34 u_2)} \quad (3.2)$$

Where, ET_o (mm/d) is the reference evapotranspiration, R_n ($MJm^{-2}d^{-1}$) the net radiation, G ($MJm^{-2}d^{-1}$) the soil heat flux density, T (^oC) the mean daily atmospheric temperature, ρ_s (kPa) the saturation vapor pressure, ρ_a (kPa) the actual vapor pressure, Δ (kPa $^oC^{-1}$) the slope of saturation vapor pressure curve, γ (kPa $^oC^{-1}$) the psychrometric constant and u_2(m/s) the wind speed all measurement was taken at 2 m height.

iv. Daily soil water content for each individual treatment were calculated based on soil water balance equation used by Hillel (1998).

$$\Delta S = P + I + U - D_w - R - ET_c \quad (3.3)$$

Where, ΔS is the change of soil water storage in 0-100 cm soil profile, P the precipitation, I the irrigated water depth, U the capillary rise from the soil profile below 100 cm, D_w the downward drainage beneath 100 cm soil profile, R the surface runoff, and ET_c is the crop evapotranspiration calculated from equation (3.1). Since no runoff (R) found even in surface flooding because of proper bound height around the sub-plots so the relevant term was neglected in calculating ΔS. Likewise upward and downward movement of water were estimated by Darcy's law (Gao et al., 2010; Kar et al., 2007).

3.2.3 Soil water dynamic

After direct measurement of weekly soil water content by TRIME, the actual weekly evapotranspiration from the treatment plots were calculated using equation 3.3 whereas, to predict irrigation scheduling the equation 3.3 were used to estimate change in daily soil water content in which ET_c were the estimated evapotranspiration taken from equation 3.1 as explained in section 3.2.2. The other soil water dynamics parameter like; soil evaporation, crop transpiration, and drainage from the treatment were simulated by HYDRUS-1D as described in section 3.2.4. The observed and simulated profile soil water content was evaluated and analyzed as described in section 3.2.5. The overall soil water dynamics parameters are presented in table 3.1.

3.2.4 Root water uptake

The sink term "S" defined by Feddes et al. (1978) as the volume of water removed from a unit volume of soil per unit time due to plant water uptake and further expansion by Van Genuchten (1987) hydraulic model introducing osmotic stress in Feddes explanation as described in HYDRUS-1D software package for simulating the one-dimensional movement of water in variably –saturated media developed by Šimůnek et al. (2013) had taken as the basic concept for this experiment to simulate root water uptake. The simulation for "Root Water Uptake (RWU)" was carried out from the date of first irrigation to the harvest time.

3.2.5 Analysis of simulated output

The analysis of variance (ANOVA) was done as explained in the section 2.7 whereas, the simulated output data obtained from model was evaluated with root-mean-square error (RMSE) by making a comparison between observed and simulated soil water content for each treatments (Han et al., 2015));

$$RMSE = [\frac{1}{n}\sum_{i=1}^{n}(C_{si} - C_{obs})^2]^{1/2} \quad (3.4)$$

Where, C_{si} and C_{obs} are the simulated and observed soil water content, respectively; n the total number of observation used for evaluation.

3.3 Interpretation of Climatic Condition

The total amount of rainfall (Table 3.1 and Fig.3.3) was less in 2014 (107.7 mm) than in 2015 (137.9 mm), also the mean average atmospheric temperature was more in 2014. Thus, 2014 winter wheat season was relatively dryer than 2015 season. These factors were found to play a major role in controlling the irrigation scheduling and total amount of irrigation water (Table 3.1) even for the same scheduling level as well as the same irrigation method in two corresponding seasons. The precipitation and mean daily atmospheric temperature during the experimental period for both cropping season (2013-14 and 2014-15) recorded from first irrigation (mid-March) to harvest (early June) at research field is presented in fig. 3.3. The micro climate changed according with irrigation method but is not included in this study. Particularly in sprinkler irrigation the atmospheric temperature drops drastically during the irrigation and expected to have decreased overall evapotranspiration.

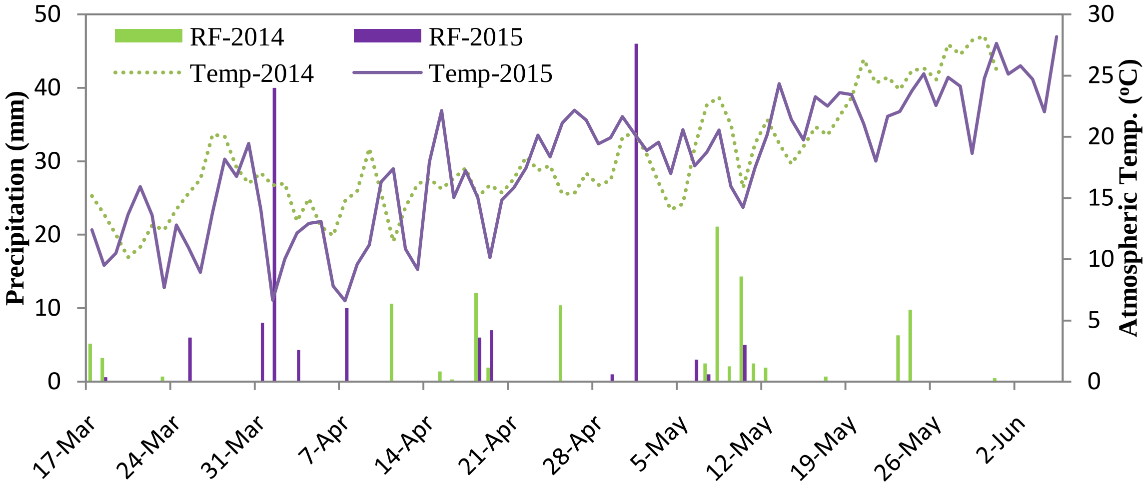


Figure 3.3 **Precipitation and atmospheric temperature for two cropping seasons**

3.4 Impact of Irrigation Management on Soil Water Dynamics

3.4.1 Irrigation quota

Total irrigation water amount applied had greatly influenced by the precipitation amount in two cropping seasons. In cropping season 2014-15 the rainfall occurred was found 30.2 mm more (Table 3.1) than in season 2013-14, which is equivalent to one irrigation amount. Because of this low rainfall in 2013-14, one additional irrigation for each treatment was required than 2014-15 cropping seasons. While considering the irrigation method, the drip irrigation wetted less surface soil and have very low water application rate. These phenomena restricted the further drainage from the root zone and reduce the irrigation amount in great amount. The treatments S1 and D1 both utilized irrigation water 33.3 % and 25% more efficiently than F1treatment in 2014and 2015 respectively (Table 3.1). Similarly, S2 and D2 both required only 75% and 83.3% irrigation amount than that of F2 for corresponding season. While irrigating winter wheat at 70% of FC, only SDI will give the satisfactory saving for irrigation amount in comparison to FI and SI. These results shows that in both dry and wet season the applied irrigation water utilization has found efficiently in SDI and SI in comparison to flood irrigation treatment. The utilization of irrigation found more efficient in dry season than wet season for both SI and SDI but the efficiency decreased with more frequent irrigation. Particularly, for wet season winter wheat cultivation, irrigation at 70% with SI and FI found causing ill effects with lowest irrigation water utilization. Thus the results verified that irrigation amount increased with increasing irrigation frequency whereas for same irrigation scheduling, FI consumed more irrigation than SI and SDI at any weather conditions.

3.4.2 Soil water content

The soil water content (SWC) for all the treatments was found to be higher in 20 to 50 cm soil depth (Fig. 3.4). In 70% irrigation scheduling treatments (IST) the SWC was higher in deep profile following the order F3>S3>D3 whereas in the upper layers the SWC was higher in D3 following the order D3>F3>S3. The SWC below 50 cm for 50% IST was very less 0.11-0.16; 0.12-0.17 and 0.13-0.18 cm^3/cm^3 in FI, SDI and SI, respectively.

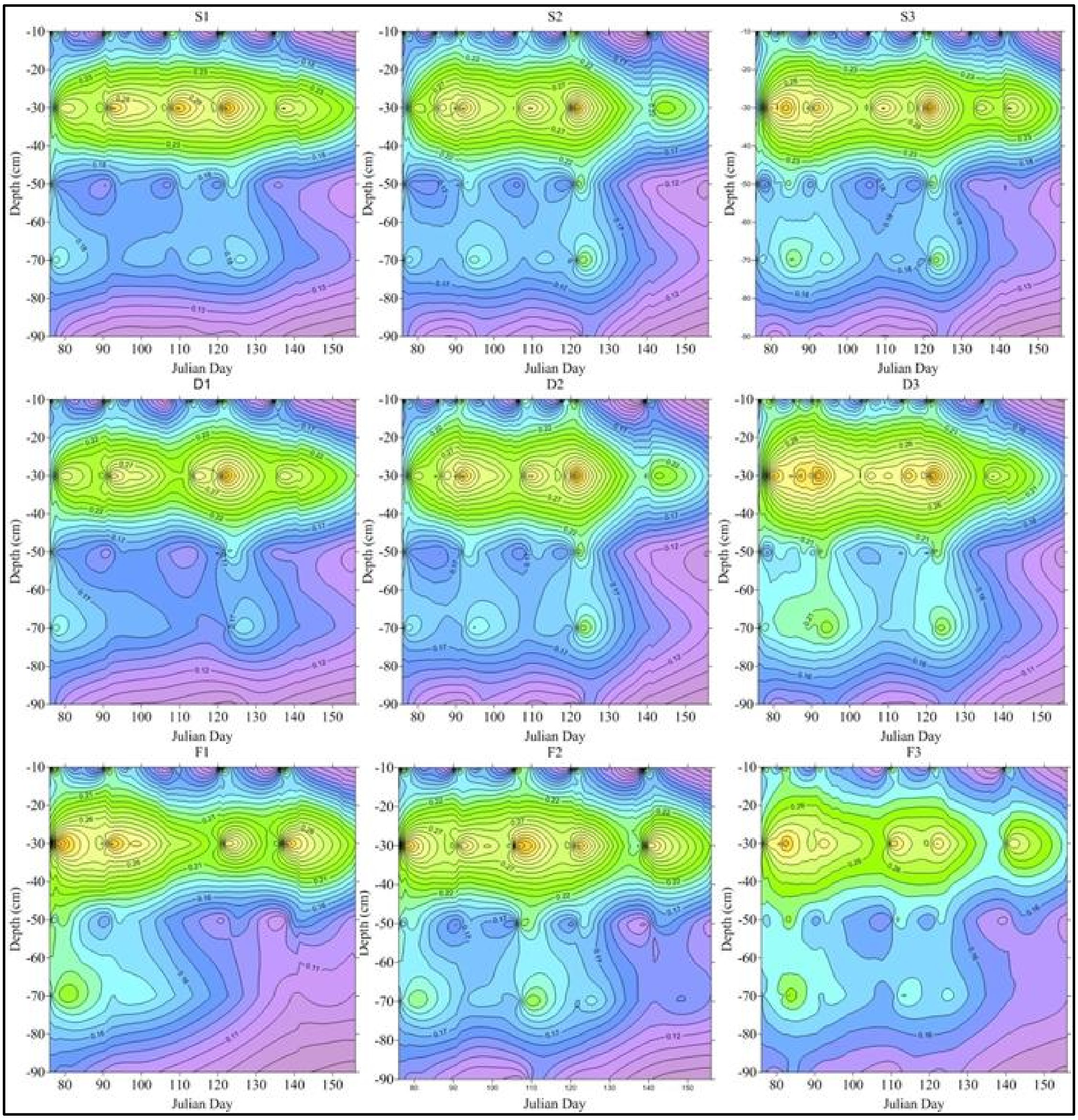


Figure 3.4 Soil water content (cm3/cm3) in the year 2015

The profile water distribution for 60% IST was found similar in all irrigation method and was found quite uniformly distributed up to 80 cm deep. The SWC from the depth of 20-50 cm was much higher for all the treatments because of highest bulk density with more loamy soil texture for the profile 20-40 cm depth. Below 80 cm the soil water content consistently shows lower in all irrigation treatments because of higher drainage capacity of sandy soil with low bulk density (Table 2.1). The results show that the average SWC in the profile above 60 cm can be maintained by SI and SDI rather than FI with different irrigation scheduling. Similar results are also found by Rawlins and Raats (1975).

3.4.3 Root water uptake (RWU)

The actual daily root water uptake (RWU) simulated for 2015 by hydrous-1D is shown in fig. 3.5. The daily simulation graph not shown for year 2014 but the total RWU from re-green to harvest for both years is presented in table 3.1. The simulation results showed that the daily RWU reached about 6 to 9 mm/d at the end of March to mid of April and at early to mid of May. Synchronizing the daily RWU with rainfall pattern (Fig.3.3) and irrigation scheduling (Table 2.3), the uptake found increases with increasing soil water availability at grain filling. Similar results have been found by (Li et al., 2014) and (Xue et al., 2003) who correspondingly found greater RWU after rainfall or irrigation and at grain filling stage.

The statistical analysis shows that the irrigation water application method significantly (α=0.05) affected the total RWU at period of re-green stage to harvest and highly significant (α=0.01) with irrigation scheduling. The total uptake in both years was found to be higher for 70% scheduling treatment and reduced accordingly with less frequent irrigation (Table 3.1). The simulation showed that, F3 used 60 mm and 90 mm more irrigation water compared to D3 to increase 22.6 mm and 57.1 mm RWU, and required 30 mm & 60 mm excess irrigation compared to S3 to increase RWU by 31.5 mm & 54.8 mm in 2015 and 2014, respectively. This shows that if winter wheat needs to be irrigated at high frequency, SDI system performs more efficient in utilizing the applied irrigation water than SI and FI even it produced shallow root. Likewise, F1 uses 30 mm and 60 mm more irrigation in 2015 and 2014 respectively to increase 28.04 mm and 26.7 mm RWU compared to D1 and increase 47.4 mm and 24.8 mm RWU with respect to S1 for corresponding years. These results indicate that the RWU has been enhanced by RLD in FI but rather than that, the irrigation scheduling and application method plays more roles which create hydraulic functions in the root zone depending on weather and soil conditions.

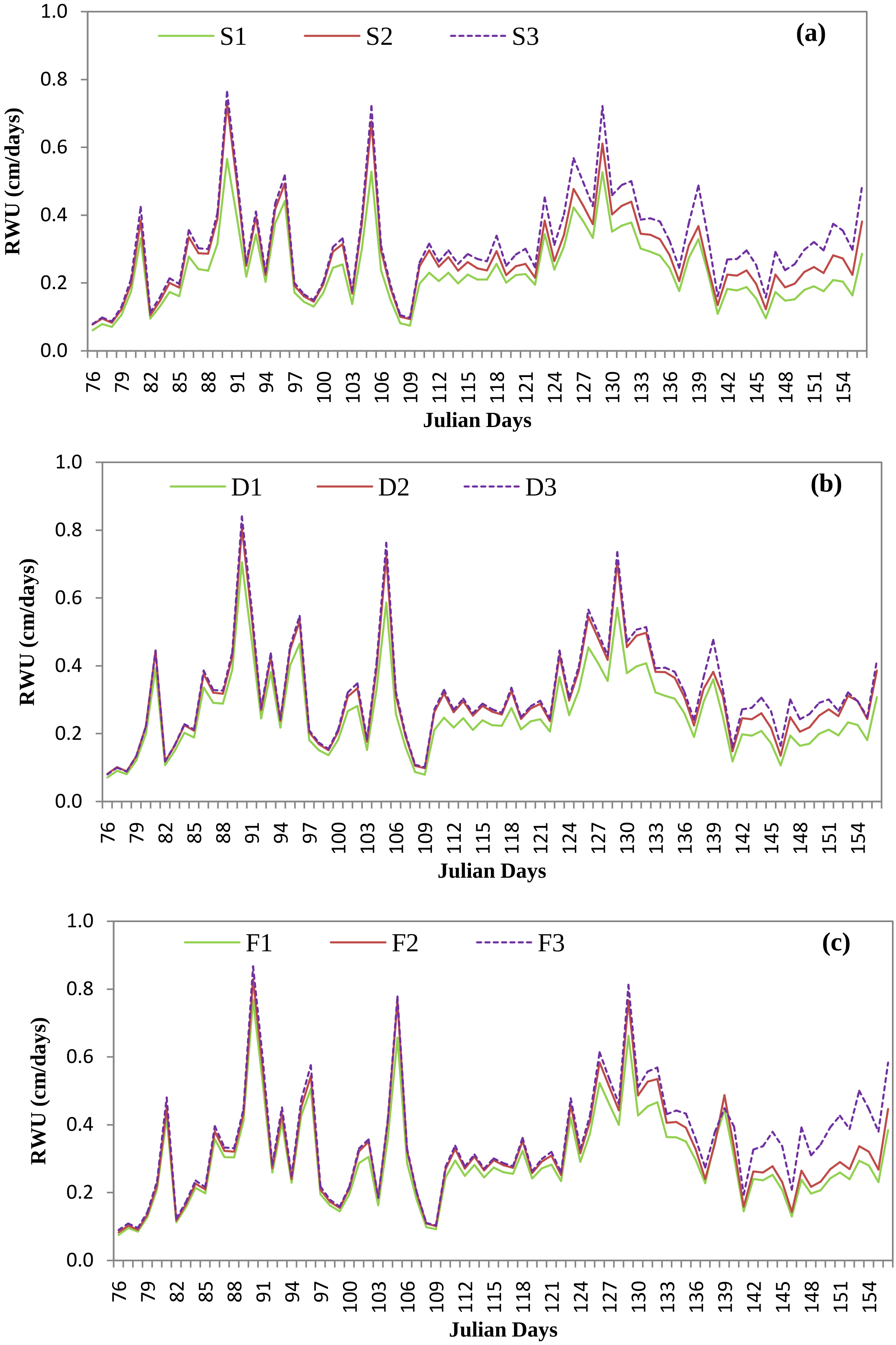


Figure 3.5 **Daily root water uptake (RWU) from sprinkler irrigation (a), surface drip irrigation (b), and surface flooding treatments (c), irrigated at 50%, 60% and 70% of FC in 2015**

3.4.4 Profile root water uptake distribution

Analyzing the profile RWU distribution as shown in fig. 3.6 (a & b) for 2014 & 2015, respectively reveal that the water uptake from top 20 cm soil layer is maximum in F3 (10.84 cm for 2015 and 10.87 cm for 2014) followed by D3 (10.33 cm) in 2015 and by F2 (8.91 cm) in 2014 and established as main uptake region which contributes about 38% to 40% of the total RWU. The uptake from the sub region 20 cm to 60 cm and 60 cm to 100 cm was 49% to 51% and 10% to 12% of the total RWU, respectively. The profile distribution of RWU shows that the uptake from 60-100 cm is much less compared to 20-60 cm. On the other hand, the high frequency irrigation treatments consistently reduces the uptake rate from the deeper zone whereas low frequency treatment increases the rate of uptake from the deeper profile hence the RWU shifted downward as the soil water content decreased in the top profile.

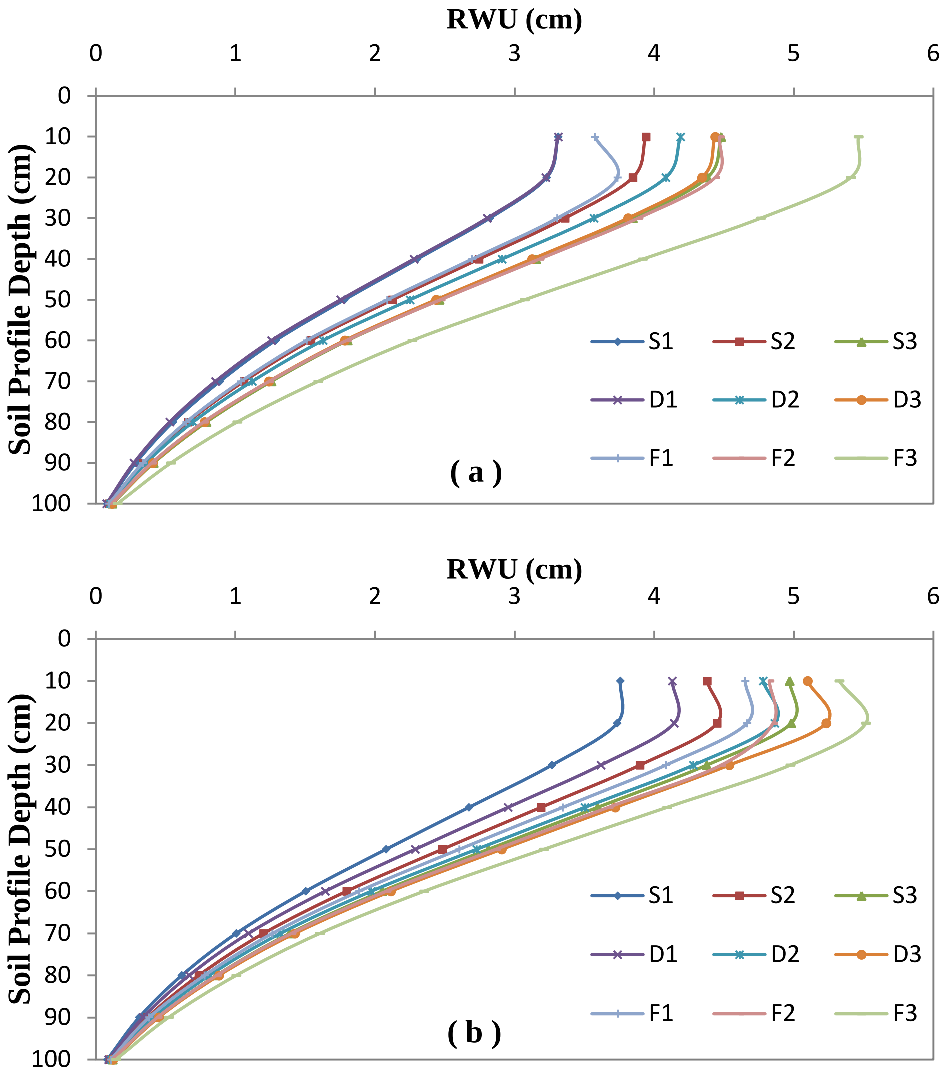


Figure 3.6 Profile root water uptake distribution in 2014 (a) and 2015 (b)

Table 3.1 Soil water dynamics in the root zone for crop season 2014 and 2015

Year	Parameters	S1	S2	S3	D1	D2	D3	F1	F2	F3
2014	Total Rainfall (R), mm	107.7	107.7	107.7	107.7	107.7	107.7	107.7	107.7	107.7
	Total Irrigation (I), mm	120.0	180.0	240.0	120.0	180.0	210.0	180.0	240.0	300.0
	Change in Soil Water Storage (S), mm	40.8	21.3	-10.4	29.9	21.5	10.3	15.7	0.9	-5.2
	Drainage (D), mm	9.1	27.8	35.8	3.9	18.6	29.4	30.0	46.1	61.5
	Evapotranspiration (ET_c), mm	259.4	281.2	301.5	253.7	290.6	298.6	273.4	302.5	341.0
	Actual Root Water Uptake (T_A), mm	165.5	197.1	227.1	163.6	209.1	224.8	190.3	227.6	281.9
	Evaporation (Es)/ ETc ratio (%)	36.2	29.9	24.7	35.5	28.1	24.7	30.4	24.7	17.3
	RMSE Value for Soil Water Content (cm/cm^3)	0.02	0.04	0.02	0.03	0.04	0.02	0.03	0.04	0.06
2015	Total Rainfall (R), mm	137.9	137.9	137.9	137.9	137.9	137.9	137.9	137.9	137.9
	Total Irrigation (I), mm	90.0	150.0	210.0	90.0	150.0	180.0	120.0	180.0	240.0
	Change in Soil Water Storage (S), mm	30.1	11.4	-15.5	38.1	21.7	10.9	41.8	17.2	-9.2
	Drainage (D), mm	-4.8	7.9	25.1	-8.9	9.6	18.7	13.5	36.8	49.4
	Evapotranspiration (ET_c), mm	262.8	291.4	307.3	274.9	300.0	310.1	286.2	298.3	319.3
	Actual Root Water Uptake (T_A), mm	190.2	226.0	256.0	209.6	247.9	264.9	237.7	256.0	287.5
	Evaporation (E_s)/ ET_c ratio, (%)	27.6	22.4	16.7	23.8	17.4	14.6	16.9	14.2	10.0
	RMSE Value for Soil Water Content (cm/cm^3)	0.01	0.04	0.05	0.01	0.04	0.06	0.04	0.05	0.07

3.4.5 Evapotranspiration (ET_C)

In both season, evapotranspiration (ETc) varied significantly (α = 0.05) for irrigating the crop with different irrigation method at different scheduling. The total ETc in both seasons for individual treatments does not varied significantly. The maximum ETc of 341 mm in 2014 and 319 mm in 2015 had occurred for F3 treatment (Table 3.1). The seasonal ET has increased with increasing irrigation amount (Lv et al., 2013b; Zhang et al., 1999) as shown by 70% IST and found excessive for surface flooding than other irrigation method. The total ET from the treatment has found similar to the result obtained by Sun et al. (2006), where he had also found maximum ET in the most irrigated treatment and lowest ET in the least irrigated treatment. The range of ET found in different treatment are similar to Li et al. (2013). Irrigation amount and ET correlated linearly and found increasing ET with increasing irrigation amount (Fig 3.7).

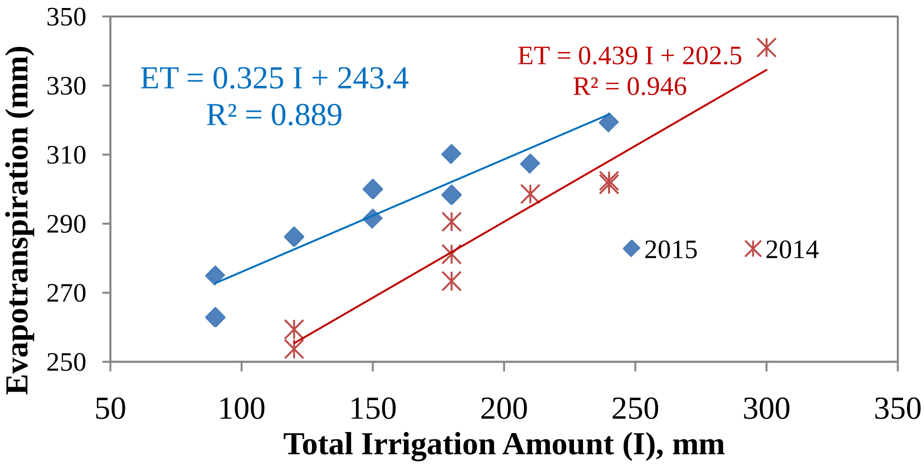


Figure 3.7 Relationships between evapotranspiration and total irrigation amount

3.4.6 Evaporation and evapotranspiration ratio

The evaporation (E) loss was found more in 2014 because of dry season and hence increases number of irrigation per treatment (Table 2.3). The evaporation (Es) to Evapotranspiration (ET) ratio found decreasing with increasing irrigation amount as described by(Yu et al., 2009). The high ratio of Es/ET in low irrigation treatments like S1, D1 and F1 was due to its smaller canopy coverage (Sun et al., 2006) and found highest in SI. This maybe because of frequent irrigation in SI and water exist in upper soil profile due to less irrigation amount per irrigation. While in SDI the wetted surface parameters was less which reduced the surface evaporation and hence finally minimize Es/ET ratio. Even Es was found more in FI after irrigation, the irrigation interval was too long as compare to SI and SDI which keeps surface dry for longer time for same irrigation scheduling and cause to reduce Es/ET ratio.

3.4.7 Drainage from root zone

The drainage from irrigated winter wheat root zone, significantly varied (α = 0.01) for applying water with different method and different irrigation scheduling. It has found that about 49.4 to 61.5 mm irrigation water deep percolated in 2015 and 2014 respectively while irrigating with surface flooding at 70% of FC and found relatively no deep percolation in sprinkler and drip irrigation while irrigating at 50% of FC. Percolation rate was increased with increasing irrigation frequent and found excess in FI treatments than SI and SDI. The result obtained was similar to Liu et al. (2013c), where he had explained that drainage from the winter wheat root zone increases with the increase in the irrigation amount.

3.4.8 Change in soil water storage

Change in soil water storage (S) in table 3.1 showed the maximum soil water depletion (SWD) for irrigating at 50% of FC in FIand found recharged of soil water when irrigating at 70% of FC in both FI and SI. This shows that if irrigating winter wheat at longer irrigation interval makes more SWD and for frequent irrigation the SWD reduced. The SWD was found least for frequent irrigation F3, S3 and D3 treatments, indicating irrigation could meet the needs of winter wheat (Sun et al., 2006). On the other hand for low irrigation scheduling (F1, S1 and D1) treatments which receives limited irrigation amount makes winter wheat to utilized stored soil water and hence cause SWD in the root zone.

3.5 Discussion

3.5.1 Profile soil water content

Soil water content depends on amount of water it received and lost. Since the climatic condition and soil characteristics were same for all the treatments the profile water distribution found distinct because of different irrigation water application methods and irrigation scheduling. The soil permeability of central root zone (20-60 cm) was found very low (Table 2.1) which may be one of the reasons that in this root zone SWC remains higher for most of the treatments. Similarly, the soil permeability below 80 cm was very high which allows free drainage and keep SWC lowest but the SWC in F3, S3 and D3 treatment was higher because of high irrigation frequency increases hydraulic head. In SI and SDI treatment, irrigation amount per irrigation was 30 mm which was properly hold in upper 60 cm soil profile because of low hydraulic head (h). Whereas, in FI 60 mm irrigation amount per irrigation create more h which easily flow through macro pores to make the lower soil profile saturated. Frequent irrigation treatment at 70% of FC provide more available water for crop growth but cause more loss in drainage because of sand below 80 cm and easy surface evaporation because flooded most of the growth period (Sun et al., 2006).

3.5.2 Root water absorption

The maximum root water absorption occurred after full vegetative growth to booting from end of March to mid-April and during heading to anthesis from early to mid-May (Liu et al., 2002) as shown in fig. 3.5. Comparing the ratio of actual root water uptake to total inflow (R+I) water in root zone (Table 3.1), it was found that the ratio is highest for F1 followed by D1>D2>S1>D3>F2>S2>F3>S3 in 2015 and for D2 in 2014 followed by S1>D1>D3>F3>S2>F1>F2>S2. In both years the uptake rate was found comparatively the highest in SDI which contains higher RLD in 0-20 cm soil profile as described by (Zhang et al., 2004a). On the other hand, the surface temperature in SDI and in low frequency irrigation treatments remains higher (Chapter 4) which prolong to surface evaporation and reduces the SWC in surface (Fig 3.4). In this condition, if the lower soil profiles have enough water, the soil moisture gradient established between the layers promotes capillary rise in night when the surface temperature becomes low (Li et al., 2010; Lv et al., 2013a). This phenomenon contributes to optimize the root water uptake and overall transpiration for shallow root developed treatments as in SDI whereas, for deep root as developed in flood irrigation or low irrigation frequency treatment water uptake directly occurred in deep soil profile where the RLD distribution plays an important role in contributing RWU (Lv et al., 2010; Zhang et al., 2009).

3.5.3 Dynamics of profile root water uptake

The profile RWU distribution pattern shows that the top 20 cm soil profile is the main uptake reason which contributes about 38 to 40% of the total RWU where the existent of RLD is higher. Even the RLD in soil profile 20 to 60 cm was comparatively less than 60 to 100 cm, the water uptake was found higher because of high available soil water content. This shows that the availability of water for crop water use is the main responsible factor for optimum RWU. The profile root water uptake in irrigation scheduling treatments with different water application methods converges as it goes deeper (Fig. 3.6). This proves that even the treatments that irrigates with high frequency and with more irrigation water, it reduces the profile water uptake. However, the uptake is more if there is the presence of dense root in the deeper soil profile as found in less irrigation schedule treatment.

3.5.4 Drainage functions

The drainage from the surface flood irrigation has been found much more than SDI and SI. One of the cheap reasons for excessive drainage from the FI treatment is that the irrigation amount. To make proper surface flooding at least 60 mm irrigation water is necessary, while for irrigating with drip or sprinkler the application amount per irrigation was considered to be taken as 30 mm. The lower application of irrigation amount in SI and

SDI keep water withstand in upper profile (Fig 3.4) because of low hydraulic head (h) where as in FI treatment more water per irrigation increase h and hence supports for drainage.

3.5.5 Analysis for evapotranspiration

The result indicates that ET of winter wheat was greatly affected by irrigation application. ET was driven by meteorological factors, crop factors and soil factors and is not only water consuming process but also an energy consuming process. The regression analysis clarify the effects of irrigation on ET, where we have found significant relationship (α =0.01) existed between irrigation water amount with ET. The relations were described for two cropping seasons with the following equation as shown in fig 3.7;

$$ET = 0.325 \times I + 243.4, \ R^2 = 0.889^{**} \qquad (3.5)$$

$$ET = 0.439 \times I + 202.5, \ R^2 = 0.946^{**} \qquad (3.6)$$

Where, ET is evapotranspiration (mm) and I the total irrigation water applied in the whole growing period of winter wheat (mm).The Es/ET ration in the beginning of the growing season was highest and gradually decreased due to canopy development. Similarly, high ration of Es/ET in treatments with 50% irrigation scheduling i.e. S1, D1 and F1 was due to its smaller canopy coverage (Sun et al., 2006), which gradually decreases with increasing irrigation frequency. However the absolute amount of evaporation was still larger at the growing phases when plant transpiration consumed most of water (Liu et al., 2002). So how to decrease the soil evaporation and make it available for transpiration through the plant is an important way to save water.

3.5.6 Relationship between root water uptake and total irrigation water

The root water uptake increase linearly with application of more irrigation water (Fig 3.8), which keeps higher soil moisture throughout growing period. The previous studies in wheat and sorghum by Meyer et al. (1990) showed that RWU rate decreased linearly as available soil water decreased. Hamblin and Tennant (1987), shows that water uptake being faster when soils were moist which supports this study results RWU Vs irrigation amount. In this manner water application method like SDI and SI plays a vital role in managing the water retention in root zone with the application of controlled amount (about 30 mm) of irrigation water which reduce the hydraulic head compare to FI system. Retention of irrigation water in soil largely depend on flow rate (time of irrigation) up to the field capacity where SDI will be the best option compare to SI and FI system.

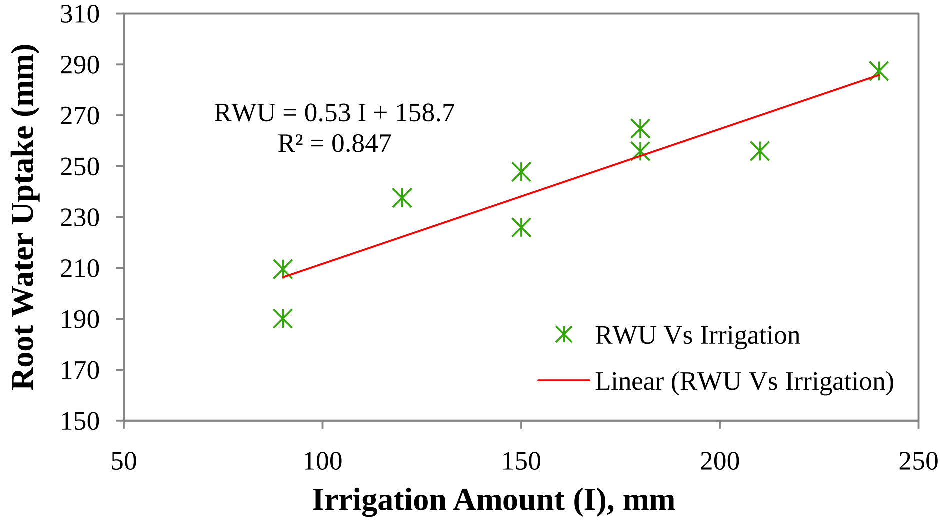


Figure 3.8 Relationship **between root water uptake and irrigation amount**

3.6 Data verification

The simulated soil water content obtained by hydrous run evaluated with the actual measured soil water content obtained in field by calculating RMSE value for each treatments are presented in table 3.1 for corresponding seasons. The RMSE value for S1, D1, F1, S2, D2 in 2015 and all treatments except F3 in 2014 shows best fitted with minimum error while a little large value for F3, S3, D3, F2 in 2015 and F3 in 2014. This may be due to high soil water content present in the corresponding treatments either after irrigation or rainfall.

3.7 Conclusion

The chapter includes the study of profile soil water dynamics for currently farmers using main irrigation methods with promising irrigation scheduling in winter wheat at North China Plain (NCP). The powerful simulation model “Hydrous-1D” for “One-Dimensional Movement of water” has been used to simulate profile soil water dynamics. The results showed that irrigation method and irrigation scheduling both influenced the profile soil water distribution pattern and profile root water uptake. Profile soil water content, which correspondingly changed with irrigation method and scheduling becomes the key factor in controlling overall irrigation water requirement by shifting the profile root water uptake. The evapotranspiration rate has significantly affected by applying irrigation water with different irrigation method at different irrigation scheduling. In the upper soil layer of 0-60 cm for all three irrigation methods, the root water uptake is seen higher with increasing moisture scheduling leaded by SDI compared to SI and FI due to higher root length density (RLD) in upper soil profile for SDI than those for SI and FI. On the other hand, the root water uptake leads in FI than SI and SDI in deep soil profile below 60 cm because of higher RLD in FI as compared to SI and SDI.

It has been concluded that soil water content which vary with water application methods and irrigation scheduling, plays an important role in determining the root water uptake and finally affects the overall soil water dynamics of winter wheat cultivation. It is very important to understand how to irrigate, how much to irrigate and when to irrigate winter wheat depending upon the weather condition for optimizing the root water uptake. About 90% of the total water uptake occurred in 0-60 cm soil profile where most of the root exists. The root water uptake converges in deeper soil profile accordingly with high frequency irrigation scheduling by different water application methods. In an overall surface drip irrigation scheduled to irrigate at 60% of field capacity perform better in both seasons keeping optimum root water uptake, save irrigation water significantly and tolerate weather and soil conditions. It is also recommended to select water application method and it’s scheduling according to weather conditions and soil properties which play an important role in changing the soil water storage and overall evapotranspiration as well as drainage from the root zone.

Chapter 4 Soil Temperature

4.1 Introduction

It is well known that soil temperatures and their profile distribution gradient in space and time, critically determine many soil-related processes such as germination, root development, biomass allocation, water and nutrient uptake from the soil (Licht and Al-Kaisi, 2005; Velten et al., 2003). Experimental soil temperature studies are few since soil temperature is difficult to manipulate, yet it is much more stable than air temperature and changes slowly making its effects easier to model and predict than those of air temperature (Gavito et al., 2001).

Luxmoore et al. (1973), studied the effects of flooding and soil temperature on winter wheat during grain filling and concluded that longer term flooding reduced yield by 15 to 23% at 15 to 17^{o}C soil temperature. He further investigated stem dry weight per tiller decreased by about 95% with increasing soil temperature from 5 to 25^{o}C for both flooding and non flooding treatments. The soil temperature affects the growth of root system components, initiation and branching, orientation and direction of growth, and root turnover. Kaspar and Bland (1992), showed that as the temperature increases, root grow faster and reaches a maximum growth rate at about 30^{o}C for maize and pecan, after which the rate begins to decrease. Soil temperature profile distribution is greatly affected by irrigation method and undoubtedly influences root water uptake directly or indirectly(Lv et al., 2013a). Bowen (1991), reported that low soil temperature limits shoot and root growth and nutrient as well as water uptake especially below 10^{o}C which is common temperature for early crop growth in temperate region.

4.2 Methodology

Soil temperatures of each treatment were measured continuously throughout the experiment period by installing a precise thermal resistors sensor connected with data logger (Fig 2.10). The thermal resistor sensors were buried into the soil at the depth of 0, 5, 10, 15, 20 and 40 cm at the same vertical hole made by 12mmdiameter soil auger. The surface (0 cm) sensor was partially buried and partial kept in air to measure the surface temperature. The time interval for data logger (TingmData Center V6.0) to record the temperature was kept as 30 minutes. The battery of the data logger was replaced every month to prevent from data lost. Before installing the resistor and data logger calibrations were made for electric current and adjusted temperature in a thermostatic water bath.

4.3 Temperature Variation with Irrigation Management

4.3.1 Surface temperature

The irrigation method and scheduling sincerely affected the surface soil temperature. The maximum surface soil temperature with irrigation scheduling for SI, SDI and FI are shown in fig 4.1 a, b, c and with different irrigation method for 50%, 60% and 70% IST are shown in fig 4.1 d, e, f respectively. The maximum temp fluctuation difference of 4.3°C was found between S1 and S3 when compared irrigation scheduling for different irrigation method and greatest temp fluctuation difference of 3.7°C between FI and SDI at 70% irrigation method respectively (Table 4.1). The maximum surface temp established highest in S1 (27.3°C) and lowest for F3 (24.2°C). The temperature in FI was found less as compared to SDI which harmonizing the result derived by (Evett et al., 1995).

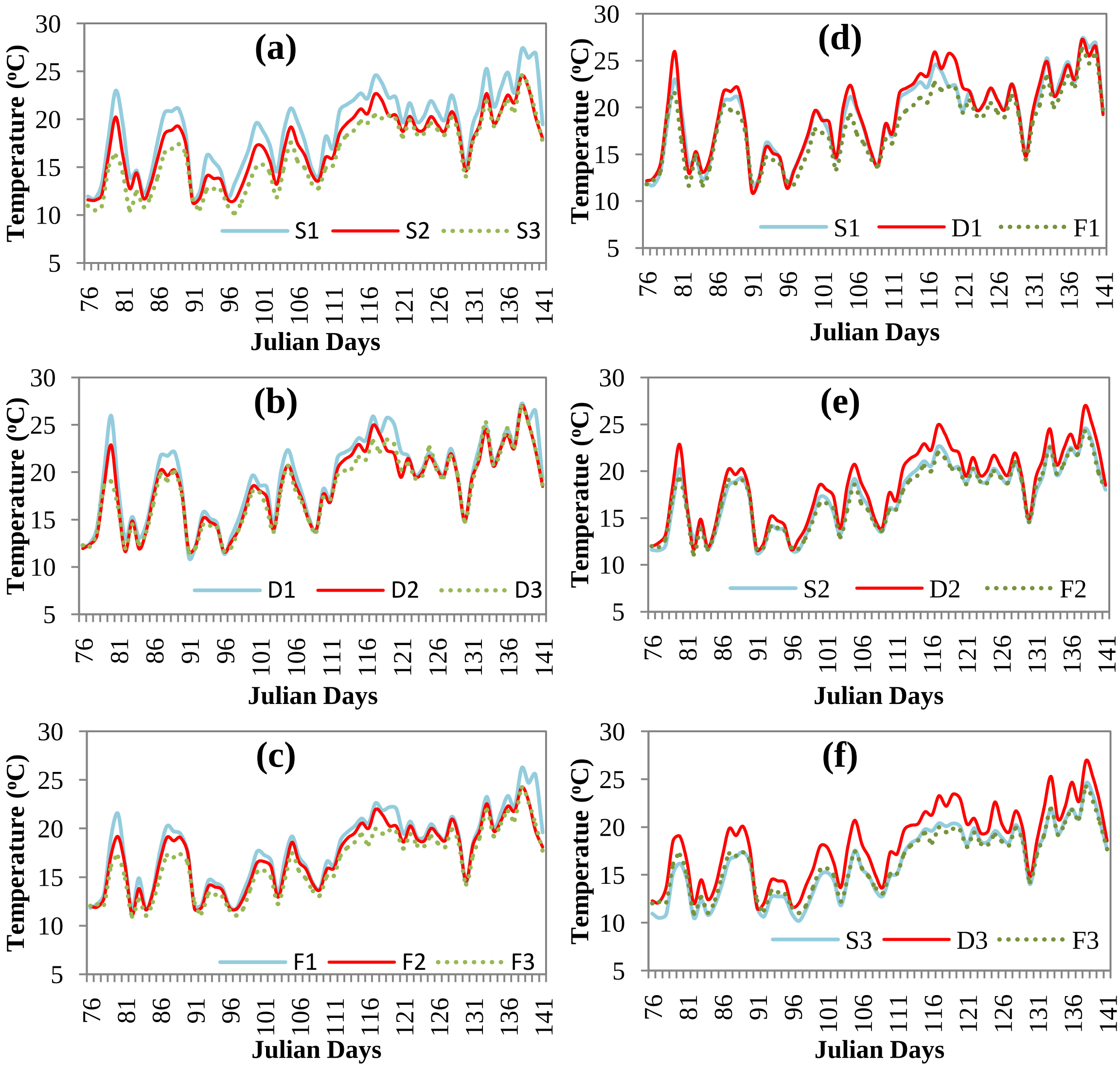


Figure 4.1 **Surface soil temperature comparison with irrigation scheduling (a, b, c) and irrigation method (d, e, f)**

The soil temperature in SDI always remains higher than SI and FI at all irrigation scheduling (Fig 4.1 d, e, and f) and the difference has found more at 50% and 70%. Less variation of surface temperature at 60% indicate that it may provide the similar environment for all irrigation method. Irrigating at 70% of FC keep lower surface temperature for all irrigation method which may cause reduction in nutrient uptake (Schachtman et al., 1998) and branching of root system (Kaspar and Bland, 1992).In general, the maximum and minimum temperature fluctuation in surface soil is in the order of SDI>SI>FI for irrigation method and 50% > 60% >70% for irrigation frequency. The optimum range of surface temp fluctuation in D1 was found to be 5.4°C higher than in F3treatment.

Table 4.1 Maximum and minimum soil temperature (°C) at different soil depth

Depth	0 cm		5 cm		10 cm		15 cm		20 cm		40 cm	
Treatment	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
S1	27.3	3.5	23.6	5.6	21.8	7.1	20.5	7.9	19.6	8.0	17.8	8.7
S2	24.5	3.3	21.6	6.2	20.3	7.2	19.3	7.7	18.7	8.1	17.0	8.5
S3	24.6	5.0	22.0	6.0	20.8	6.4	19.8	6.5	18.7	8.1	17.4	8.8
F1	26.2	4.7	25.0	5.7	22.2	7.2	20.4	8.0	19.7	8.4	17.9	8.9
F2	24.3	5.1	25.5	4.3	22.4	6.1	21.0	7.3	19.4	8.0	17.5	8.8
F3	24.2	5.3	21.5	7.1	19.8	7.8	18.9	8.3	18.3	8.6	16.8	8.9
D1	27.2	2.9	21.7	6.5	20.0	7.5	19.2	8.0	18.3	8.2	17.1	8.6
D2	27.0	4.6	21.4	7.2	19.9	8.0	19.1	8.2	18.3	8.5	17.2	9.0
D3	26.9	4.2	25.6	5.4	22.2	7.3	20.2	7.8	18.9	8.4	17.5	9.0
Fluctuation Range	24.3-19.0		21.2-14.2		16.3-11.9		13.7-10.6		11.6-9.7		9.1-7.9	
Maximum Range Difference	5.4		7.1		4.4		3.1		1.9		1.2	

4.3.2 Profile temperature

The profile soil temperature of all treatments presented in fig 4.2(a) and fig 4.2(b) respectively shows the maximum and minimum temperature obtained during experiment time. The maximum or minimum soil temperatures do not found more variation in deeper soil profile, either irrigating with different irrigation method or different irrigation scheduling (Table 4.1). The daily soil temperature compared in surface soil (Fig 4.3 a) and deepest (40 cm) soil (Fig 4.3 b) was clearly observed and found that soil temperature decreases with depth. The temperature fluctuation has found decreasing with deeper soil profile except at 5 cm soil depth where it has found more fluctuation than at surface. It may be because of easy heat transfer and stored solar energy for longer duration in the adjacent layer whereas, at surface soil the temperature rises quickly and fall suddenly if the weather changed for short time. The sensor measuring the surface temperature was kept at surface and the time interval of each temperature data was kept 30 minutes. That is at each 30 minutes a single instantaneous temperature data was recorded. At 40 cm deep soil profile, the range of temperature variation was less than 1.2°C with the highest temperature fluctuation in S1and the lowest in F3.The maximum temperature observed at depth of 0, 5, 10, 15, 20 and 40 cm were found 24.3, 21.2, 16.3, 13.7, 11.6 and 9.1°C respectively in D1, F2, F2, F2, S1, and S1 treatments. Similarly, the minimum temperature at corresponding depth were found 19.0, 14.2, 11.9, 10.6, 9.7 and 7.9°C respectively in F3, D2, D2, F3, F3, F3. The graphical representation of profile soil temperature for maximum value in fig 4.2(a) shows that the temperature gradually decreases with depth in all treatments whereas profile for minimum value in fig 4.2(b) shows increasing soil temperature with deeper soil.

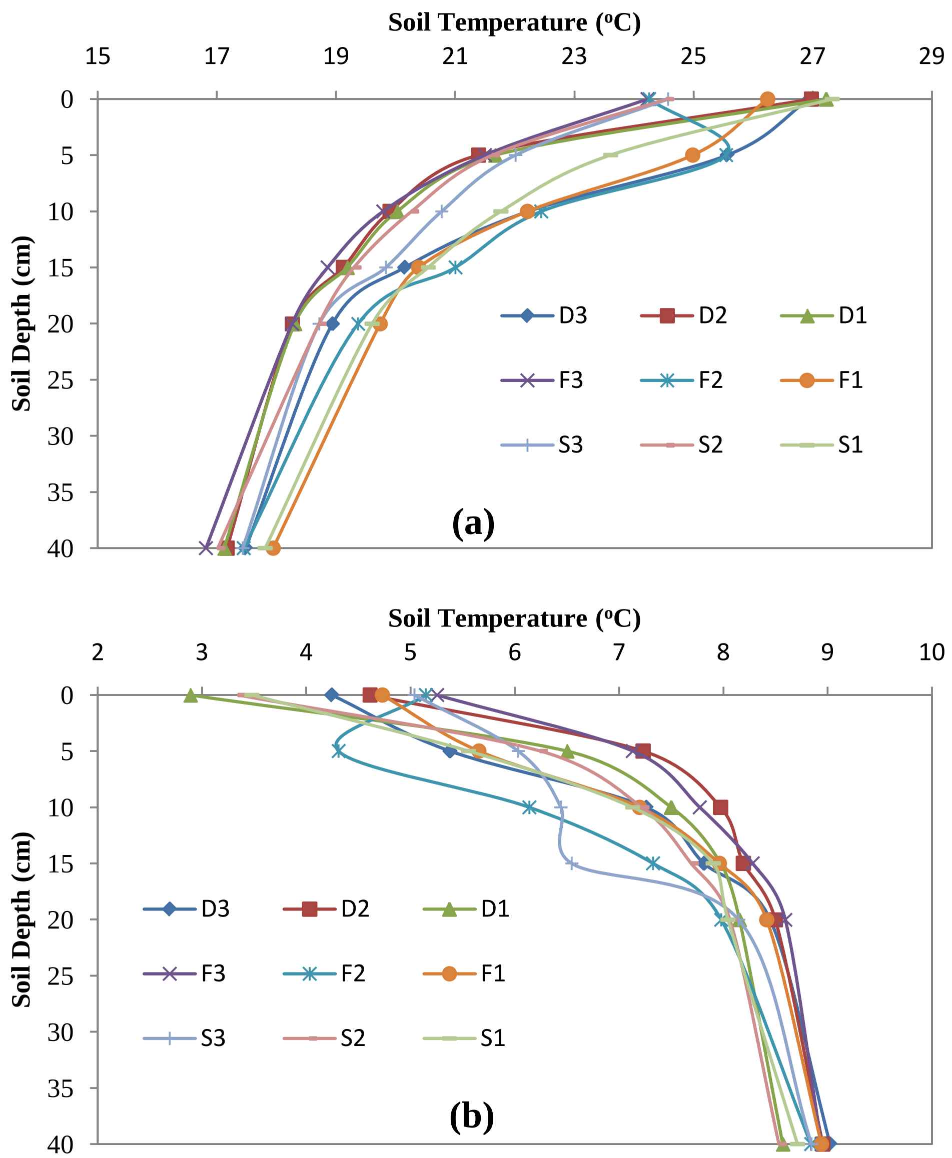


Figure 4.2 Profile soil temperature maximum (a) and minimum (b)

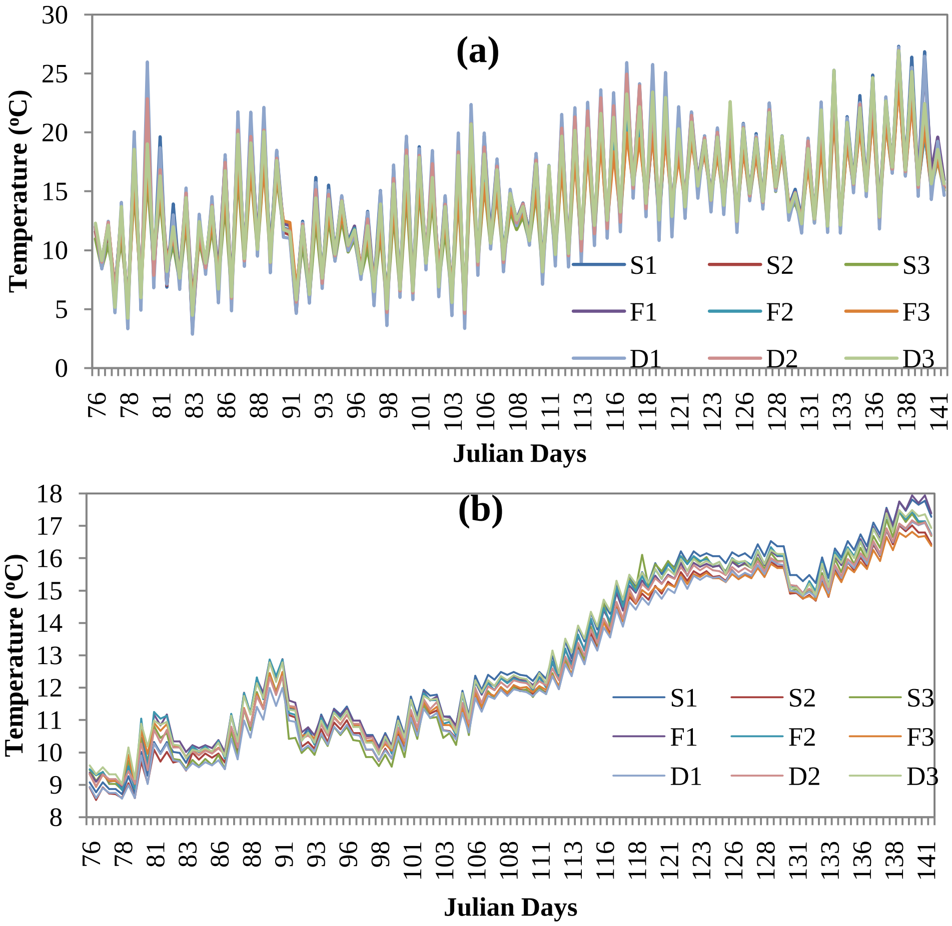


Figure 4.3 **Comparison of surface temperature (a) and deepest 40 cm (b) soil temperature**

4.4 Conclusion

The surface soil temperature fluctuates significantly because of very low SWC, which allowed increasing the temperature quickly with less solar radiation as compare to the temp fluctuation at deeper soil profile (Fig 4.3). The soil temperature found higher in SDI and lowest in FI as explained by (Evett et al., 1995) who predicted warmer soils with SDI compared to surface irrigation. From the results it has been concluded that the irrigation scheduling highly affects the top soil temperature may be due to different vegetative growth at different irrigation scheduling. In deeper soil profile the temperature variation was less either irrigating with different irrigation methods or different irrigation scheduling. The higher frequency of irrigation treatments D3, F3 and S3 keep top soil at lower temperature than the low frequency irrigation D1, F1 and S1 because of longer duration of wet soil which absorbs the generated solar heat as well as higher canopy coverage. The range of temperature variation in the soil profile was found similar to the (Lv et al., 2013a). Thus it is very necessary to maintain the temperature gradient between surface and deeper soil.

Chapter 5 Root Growth and Development

5.1 Introduction

The study of root physiologically vigorous roots systems are as essential as vigorous shoots for successful plant growth because root and shoot growth are so interdependent that one cannot succeed without the other. This chapter will focus briefly the root growth and structure, and development of root system in relation to water and mineral absorption. Knowledge of root morphology is important because it affects the pathway and resistance to water and solute movement (Kramer and Boyer, 1995). The profile root distribution and its morphology have been studied by using WinRHIZO software and professional root scanner system. The effects of three irrigation water application methods; sprinkler irrigation (SI), surface drip irrigation (SDI) and surface flood irrigation (FI) with combination of three irrigation scheduling (section 2.4.2) were studied for root growth and its development in 1 m vertical soil profile.

The studies on root morphology usually keep less attention because of being underneath the soil surface and tedious measurement jobs (Ephrath et al., 1999; McMichael and Taylor, 1987). Root as an anchorage, functions as an entry point of water and mineral nutrients for crop to produce grain as well as works as sensors of water stress, and possess many synthetic functions of shoot cells (Kramer and Boyer, 1995). Thus, better understanding of root morphological growth and root water uptake pattern in soil profile is very important for successful crop growth and maximum grain production (Coelho and Or, 1999; Roose and Fowler, 2004; Samson and Sinclair, 1994). Zuo et al. (2004), collected wheat root length density (RLD) information from several literatures and concluded that RLD is an important parameter to model water and nutrient movement in the vadose zone and to study soil-root-shoot-atmosphere interactions. Various techniques have been developed to monitor root dynamics under field conditions. The excavation techniques, including soil cores, have long been considered to give reliable estimates of root morphology (Samson and Sinclair, 1994).

Many researchers have correlated root growth and water uptake in different soil moisture regime. The amount of soil water absorbed by plant roots not only depends on soil physical characteristics but also have greater influences of profile root growth feature (Yang et al., 2006). Non-irrigated plants have thicker roots, less roots near the soil surface, and more at depth (Rowse, 1974). Li et al. (2014), concluded that root water uptake rate of maize increased after rainfall or irrigation. Xue et al. (2003), found winter wheat root continued to grow up to 2 m depth until booting stage and concluded that root water uptake rate decreased as available soil water decreased. The root sampling result by (Zhang et al., 2004a) showed that winter wheat have a profile root system with an average maximum rooting depth of 2 m and most of the root system is concentrated in the upper 40 cm of soil. This is why the roots in the top layer of soil play an important role in soil water uptake. The root development of winter wheat influenced by soil moisture, Kmoch et al. (1957) reported that a dense network of roots developed in soil when soil moisture tension was above 15 atmospheres and observed roots at a depth of 13 feet for favorable moisture conditions. Maximum root growth in the subsoil significantly improved soil water supply to the crop by shifting root growth downward during the growing period due to water depletion in surface soils (Torreano and Morris, 1998). On the other hand, soil temperature affects the growth of root system components, initiation and branching, orientation and direction of growth, and root turnover. Kaspar and Bland (1992), showed that as the temperature increases, root grow faster and reaches a maximum growth rate at about 30^{o}C for maize and pecan, after which the rate begins to decrease.

Li et al. (2010), compared three irrigations scheduling at jointing, heading and milking in winter wheat, concluded that 1 time irrigation at the jointing stage caused an increase in the root length density in > 30 cm deep soil profile than 2 or 3 times irrigation at the other growth stages. Lv et al. (2010), concluded that irrigation method influences the winter wheat root development even for same the irrigation schedule. Camposeo and Rubino (2003), concluded from an experiment on autumn-shown sugar beet that root length density along the soil profile decreased over 76% by decreasing irrigation frequency. Below and above ground biomass, limited by water stress more severely than nutrient stress (Fabião et al., 1995) whereas root initiation reduces as the depth increases (Torreano and Morris, 1998) if adequate water can be accessed by surface roots.

5.2 Methodology

5.2.1 Root sampling

To study the morphology of root system in the soil profile, each 10 cm of soil core was taken as a sample from soil surface downward to 100 cm depth by using a root auger having internal diameter of 6.91 cm and outer diameter of 7 cm. The samples were taken at the center of row as well as at the middle part of two consequent rows from each treatment (Lv et al., 2010). The core samples (Volume = 375.01 cm^3) taken were carefully transferred from auger to net matted bag as shown in fig 5.1 and sample treatment with depth were tagged written with permanent marker for each sample bag. The root samples were collected 2 times in 2013-14 and 4 times in 2014-15 at different crop growth stages.

Figure 5.1 Root sampling by root auger and transferring it to net bag

5.2.2 Root cleaning and debris separation

The sampled roots bag kept in the water until (12 hr) all the soil clods detached from the roots. The soils were flushed with house pipe at low pressure (Fig 5.2) and all clean roots were transferred into a sieve (0.25 mm^2 mesh size) suspended in trough partially filled with water (Fig 5.2). The live wheat roots (white or pale brown) from the sieve were picked by tissue forceps and collected it into the transparent plastic cup with water for scanning (Guan et al., 2015) as shown in fig 5.2.

Figure 5.2 Root cleaning, debris separation and transfer it to transparent plastic cup

5.2.3 Root morphological measurement

WinRHIZO Reg. 2007d (Regent Instrument Inc.) software was used to analyze the roots morphologies, root length, average root diameter, surface area of roots, projected area of roots, root volume, tips, forks and crossings from the scanned image of clean washed root obtained from EPSON PREFECTIONTM V700 Photo Flatbed Scanner-6400 dpi x 9600 dpi (Guan et al., 2015) as shown in fig 5.3. Root length density (RLD) was calculated from the obtained root length divided by the sample core volume (Volume = 375.01 cm^3).

Figure 5.3 Root scanning with EPSON V700 flatbed scanner

5.2.4 Root biomass

Roots were sampled as described in section 5.5.1., and then the samples were dried at 70^{o}C for 48 hour (Kätterer et al., 1993) after completion of its scanning as described in section 5.2.2. The hot air oven dried roots were weighing by electronic balance (accuracy up to 4 decimal) to determine the root biomass.

5.2.5 Installation of Mini WinRHIZO TRONtube

Mini WinRHIZO TRON transparent tube was installed nearly one month after seeding when crown roots have been established. The mini RHIZO TRON tube (ϕ = 63 mm) of 200 cm long was inserted at an angle of 45^{o} in the soil pre drilled cavity made with screw type soil auger of diameter equals to the outer diameter of tube. Two tubes for each treatment subplots were installed each at either side of the crop row. The precaution has been made in drilling the cavity so that the tubes just become tight fittings in it. About 30 cm tube was left above the surface soil without penetrating into the soil to anchor the WinRHIZO TRON camera. The fine 8 gauge diameter hole was made in the outer surface of the tube about 5 cm below from top so that the camera holder tube can make easy anchorage by inserting camera looker fitted in the holder tube. The back stitching tape were rapped from the surface to the top of the WinRHIZO TRON tube including its lid to prevent light entering into the tube. All the installation procedure is show in the fig 5.4.

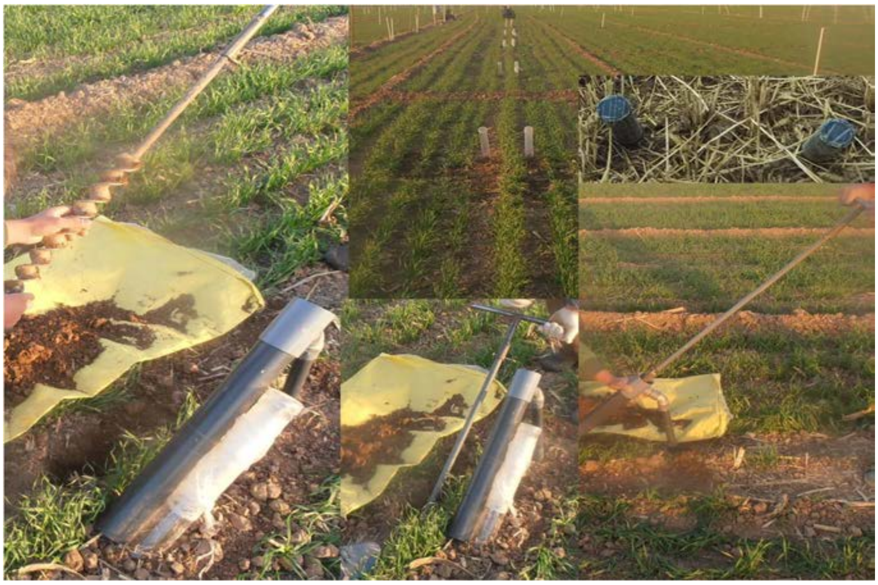


Figure 5.4 Installation of Mini WinRHIZO TRON tube

5.2.6 Root growth measurement by Mini WinRHIZO TRON

The non-destructive measurement of root turnover (root growth, death root and subsequent decomposition of the dead roots) was determined by using minirhizotron technique (Fig 5.5). The measurement includes a set of computer with software connected to camera system fascinated in long handle along with miniature accessories powered by 12 volt battery. The image location and camera depth position were noted in the field book.

Figure 5.5 Non-destructive root measurement by WinRHIZO TRON

5.2.7 Image analysis of WinRHIZO TRON measurement

The objective of minirhizotron measurement was to know the root turnover (root growth, death root and subsequent decomposition of the dead roots) from non-destructive roots which need to analyze the image taken by rhizotron camera using the WinRHIZO TRON MF V. 2007d, in soil root measurement. Due to extensive time consuming process of root turnover analysis, the study being limited to see the root growth depth, which helps in root sampling depth as described in section 5.2.1. However, the morphology of destructive root image analysis was done as described in section 5.2.3.

5.3 Impacts of Irrigation Practices on Root Growth and Development

5.3.1 Root growth and distribution

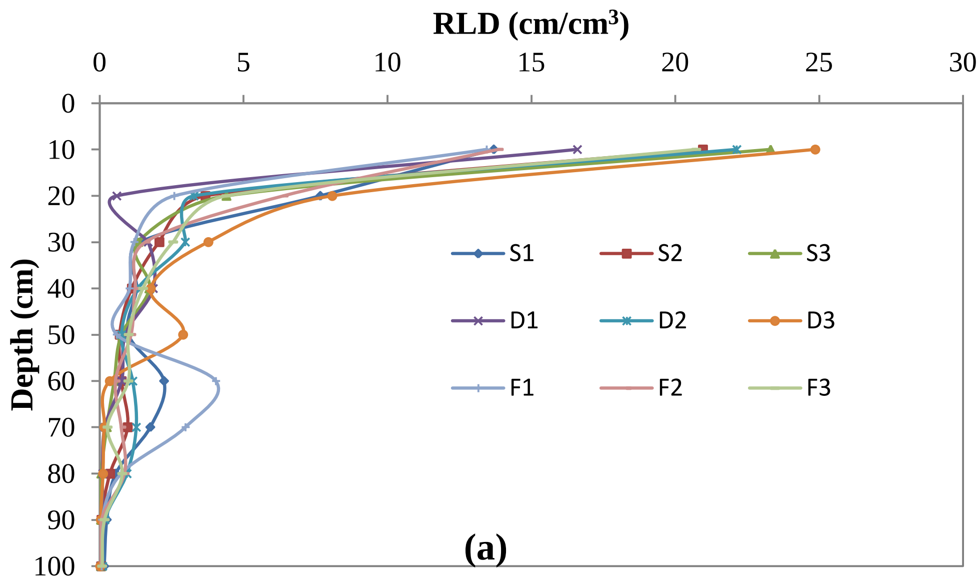
The detailed root length density (RLD) at 0-20; 20-60; and 60-100 cm for both cropping seasons with different measurement date as shown in table 5.1 revealed that the maximum RLD occurred at flowering stage. In year 2015, the SDI with high irrigation scheduling treatment (D3) generated denser root 17.88 cm/cm^3 followed by F3 (15.76 cm/cm^3) and S3 (15.47 cm/cm^3) in early stage and reached the maximum RLD of 22.06 cm/cm^{3}in D3 at flowering leading the same treatments F3 (20.29 cm/cm^3) and S3 (20.12 cm/cm^3). The root length density (RLD) distributions at flowering are shown in fig. 5.6 for corresponding year experiment. The SDI also enhanced RLD growth rate rather than FI and SI in the upper soil profile but produced less RLD below 60 cm depth. The growth rate leads by SI and FS after booting but do not compete with total RLD produced by SDI for respective scheduling in top soil which follows the similar result obtained byYang et al. (2006), and Yao (2005). The RLD below 60 cm was found highest in F1 (2.80 cm/cm^3) following the order F>S>D with 50%>60%>70% irrigation scheduling except SDI at 60% (D2, 2.17 cm/cm^3) which shows greater RLD than F2 (1.94 cm/cm^3) and S2 (1.91 cm/cm^3). The profile RLD pattern in the year 2014 are quite similar to 2015, which follows the pattern D3>S3>D2>F3>S2>S1>F2>D1>F1 in 0-20 cm depth, more or less similar in 20-60 cm and the order in 60-100 cm deep was found as F1>S1>D2>F3>F2>S2>D1>S3>D3 at flowering stage as shown in fig. 5.6 (a) and 5.5 (b) for 2014 and 2015, respectively.

Table 5.1 Root length density (cm/cm^3) in 2014 and 2015 measured at different soil depths and at different date (crop stage)

	Root Length Density (cm/cm^3), 2015											Root Length Density (cm/cm^3), 2014					
Depth	0 -20 cm				20 - 60 cm				60 -100 cm			0 -20 cm		20 -60 cm		60 -100 cm	
Date	3/18	4/9	5/6	6/6	3/18	4/9	5/6	6/6	4/9	5/6	6/6	4/30	5/30	4/30	5/30	4/30	5/30
S1	8.31	11.05	14.13	6.96	0.80	0.98	0.98	0.85	1.01	2.31	1.68	10.68	5.26	0.93	0.80	1.25	0.90
S2	9.23	14.27	16.49	10.35	0.89	1.18	1.23	1.16	0.66	1.91	1.57	12.32	7.73	0.97	0.91	0.55	0.45
S3	9.58	15.47	20.12	11.99	1.02	1.26	1.35	1.32	0.38	1.21	0.99	13.87	8.26	0.96	0.94	0.23	0.19
D1	8.40	12.29	14.23	10.05	0.82	1.13	1.15	0.92	0.42	1.81	1.22	8.60	6.07	1.11	0.89	0.30	0.20
D2	9.35	15.33	17.00	11.04	1.12	1.39	1.54	1.41	0.83	2.17	1.59	12.71	8.25	1.26	1.16	0.91	0.67
D3	10.89	17.88	22.06	14.93	1.28	1.71	1.83	1.60	0.22	0.81	0.62	16.48	11.16	2.11	1.84	0.17	0.13
F1	8.17	10.47	14.02	6.68	0.66	0.76	0.71	0.43	1.36	2.80	2.23	8.02	3.83	0.71	0.43	1.98	1.58
F2	8.68	12.69	14.59	10.28	0.97	1.21	1.31	1.22	0.70	1.94	1.57	10.13	7.14	0.98	0.92	0.56	0.46
F3	10.87	15.76	20.29	13.52	1.16	1.41	1.54	1.41	0.66	1.84	1.34	12.56	8.37	1.27	1.17	0.58	0.42

Table 5.2 Root morphology at flowering stage in 2014 and 2015

Year	Measurements	S1	S2	S3	D1	D2	D3	F1	F2	F3
2014	Total Projected area (m^2/m^3)	10.8	11.6	12.2	8.08	15.2	17	7.62	11.3	13.1
	Total Surface area (m^2/m^3)	34	36.6	38.4	25.4	47.9	53.4	23.9	35.5	41.1
	Average Diameter (mm)	0.232	0.210	0.213	0.229	0.255	0.226	0.218	0.225	0.231
2015	Total Projected area (m^2/m^3)	12.8	15.6	17.3	12.8	16.6	21	12.9	13.9	18.3
	Total Surface area (m^2/m^3)	40.1	49	54.5	40.1	52.3	65.9	40.5	43.8	57.5
	Average Diameter (mm)	0.241	0.282	0.282	0.287	0.263	0.278	0.303	0.274	0.270



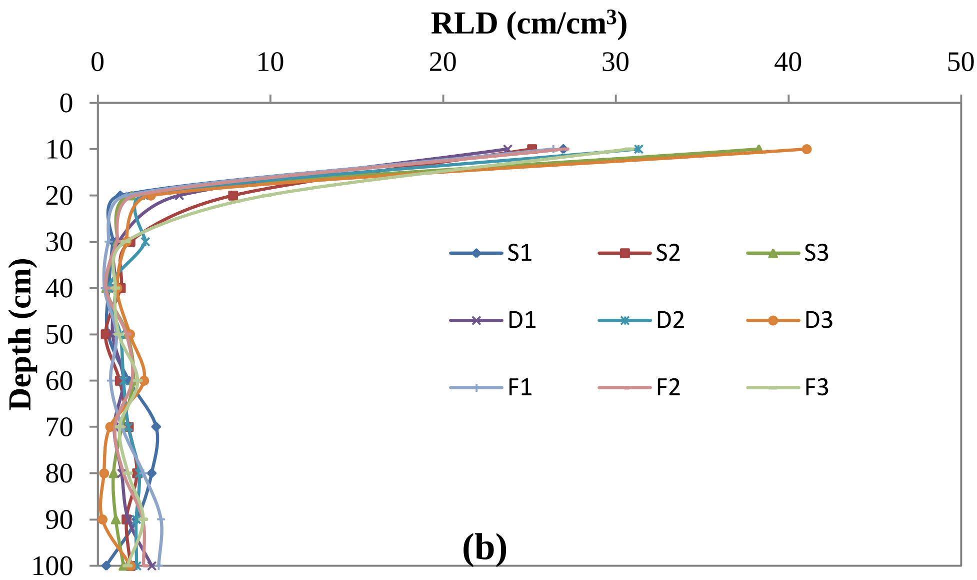


Figure 5.6 **Profile root length density (RLD) at flowering in 2014 (a) and 2015 (b)**

5.3.2 Root diameter

The average diameter of the root sampled from 1 m at flowering (Table 5.2) shows highest in D2 (0.255 mm) followed by S1 (0.232 mm) for 2014 and in F1 (0.303 mm) followed by D1 (0.287 mm) for 2015. The lowest diameter was found in S2 (0.210 mm) and S1 (0.241 mm) for corresponding years. Two years result are not found similar and do not followed any sequential trained in either season, however the thicker diameter was found in low frequency irrigation treatment and thinner in high water applied treatments.

5.3.3 Root surface area and projected area

The greatest value for total root surface area (SA) were found 53.4 & 65.9 m^2/m^3 in D3 for cropping season 2014 and 2015 and lowest value 23.9 & 40.1 m^2/m^3 in F1 & D1, respectively (Table 5.2) following the similar pattern as followed for root length density. The same order was found for projected area (PA) as in root surface area.

5.3.4 Root biomass

The highest root biomass 491.7 g/m^2 obtained at flowering stage in 2015 was found for D3 in 0-20 cm followed by F3 (465.3 g/m^2) and S3 (387.3 g/m^2) and lowest in F1 with 252.3 g/m^2 (Table 5.3). The dry biomass of root significantly varied (α=0.05) with different irrigation scheduling but didn't vary significantly with irrigation methods and follows the similar pattern as it attained for root length density. The dry mass pattern in 20 to 60 cm depth are found as D3>F3>D2>S3>F2>S2>D1>S1>F1 nearly similar to the pattern found for RLD. In the deeper soil profile (60-100 cm) biomass does not vary significantly, however the highest dry weight was found in F1 (154.1 g/m^2) followed by S1 (65.8 g/m^2). The weight of biomass for 0-20; 21-60 and 61-100 cm for the year 2014 and 2015 are shown in table 5.3. The total root biomass in the soil profile was found similar to the result obtained by Yang et al. (2006).

Table 5.3 Dry weight of root bio-mass (g/m^2) in different soil profile at flowering

Year	Depth (cm)	S1	S2	S3	D1	D2	D3	F1	F2	F3
2014	0-20	234.9	235.4	304.4	174.3	281.2	315.6	154.8	226.1	263.7
	21-60	17.7	18.6	18.4	25.5	28.3	32.6	11.0	21.3	31.0
	60-100	17.8	7.4	5.2	5.4	15.7	3.2	39.6	8.4	13.2
2015	0-20	298.4	371.3	387.3	362.7	372.5	491.7	252.3	364.8	465.3
	21-60	22.6	23.8	29.1	23.4	29.9	49.6	22.1	28.6	43.4
	60-100	65.8	43.7	40.1	40.6	50.0	32.8	154.1	46.5	43.7

5.4 Discussion

5.4.1 Root length density distribution

In SDI for each irrigation, the amount of water applied was kept low (30 mm) with longer application time which leads upper 60 cm soil profile to hold almost all irrigation water causing to shift RLD upward compared to other irrigation methods (Fig. 5.6 a & 5.6 b and Fig. 3.4). In surface flooding, large amount of water applied once and increase in the hydraulic head shifted the moisture downward which supports root system to move downward (Li et al., 2010). Whereas, irrigating winter wheat at 70% of FC, the SWC above 60 cm always leads higher and may have less aeration which tends root systems stay in the upper 20 cm (Zhang et al., 2009). Irrigation schedule at 50% of FC increases the surface temperature producing more evaporation which makes water deficit in the upper profile and forces the root growth downwards. Thus from the results we concluded that the dense root systems exist in upper layer when irrigation scheduling set at 70% and in the lower profile when scheduled at 50 %. Similar results have been found by (Li et al., 2010).

5.4.2 Root biomass variation

The frequent irrigation scheduling (70% of FC) produces significantly more root biomass than less frequent irrigation scheduling (50% of FC). This may be due to the soil surface temperature variation (Fig. 4.3 a) in different irrigation scheduling as described by Vincent and Gregory (1989). The biomass produced in F1 was found lowest for 0-60 cm which also provides evidence that for deficit SWC with relatively higher temperature the dry root biomass reduces significantly (Torreano and Morris, 1998).

5.4.3 Relationship of root length (RL) with total irrigation water and RWU

The total root lengths (TRL) increase linearly with application of more irrigation water (Fig 5.7). On the other hand, RWU correlate linearly with TRL and found positive uptake with increasing RL (Fig 5.8). Hamblin and Tennant (1987), says the uptake accelerate where root length extension was most rapid which supports the relationship obtained for TRL Vs RWU. This can be summarizing as the increased irrigation amount will increases TRL production, which influences to increase RWU. Xue et al. (2003), also observed that water extraction was significantly limited by root density. Since higher application of irrigation water also influence the drainage with nutrient depletion from root zone, it is necessary to maintain irrigation water just to retain in root zone which supports to increase TRL and hence increase RWU.

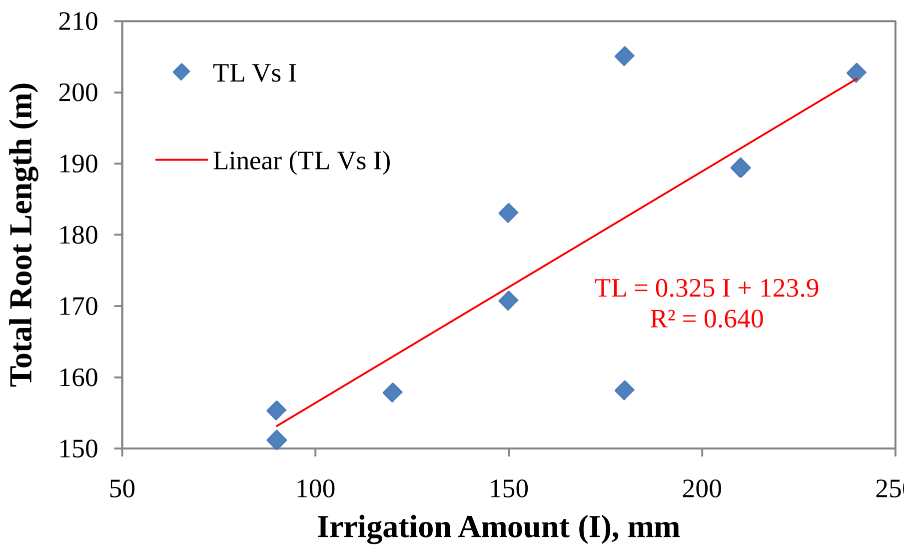


Figure 5.7 Relationship of root length density with total irrigation amount

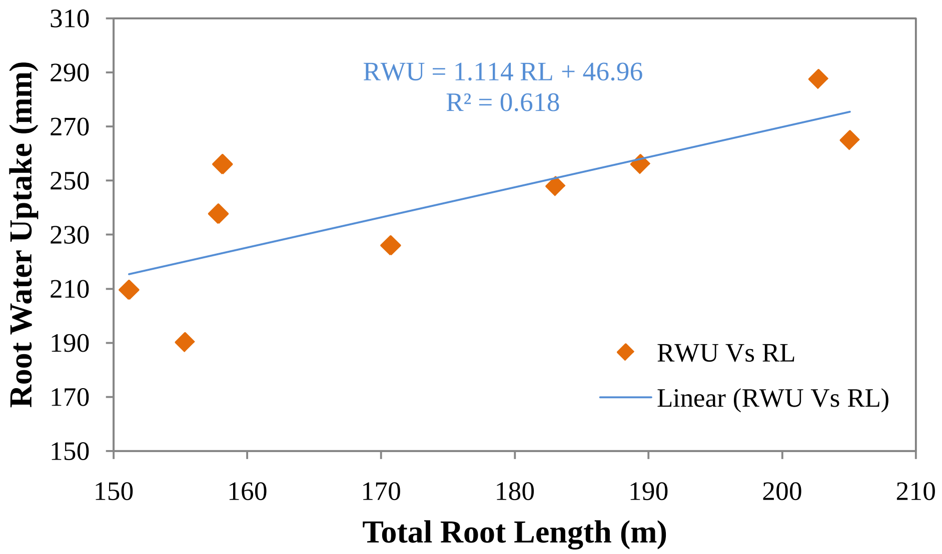


Figure 5.8 **Relationship of root water uptake Vs total root length**

5.5 Conclusion

The results showed that irrigation method and irrigation scheduling both influenced the root growth, its turnover, and profile distribution pattern. Soil surface temperature, which correspondingly changed with irrigation method and scheduling becomes the key factor in controlling root branching and downward growth. Higher root length density (RLD) in upper soil profile for SDI is seen higher with increasing moisture scheduling in the upper soil layer of 0-60 cm for all three irrigation methods as compared to SI and FI. On the other hand, RLD leads in FI than SI and SDI in deep soil profile below 60 cm because of higher soil water content in FI in deeper soil. The root distribution pattern will be helpful to make decision in irrigation scheduling. Once the existence of root is known we can easily predict how much irrigation water will be useful and which irrigation water application method can be adopt to achieve the higher water use efficiency. Since root system in soil profile is only one of the inlets for crop water and nutrient absorption so their growth and turnover described in this chapter will be helpful for good irrigation water and nutrient management practices.

Chapter 6 Crop Development and Grain Yield

6.1 Introduction

The North China Plain (NCP) is one of the most important regions for grain production in China. However, its agricultural system is being significantly affected by ongoing climate change and is becoming vulnerable with water shortage. In this region, irrigation is only one possible key to boosting the crop yield and make NCP for sustainable agriculture development. Winter wheat (*Triticum aestivum* L.) as mention before is one of the major crops in NCP, where water shortage is the most important limiting factor for wheat production in this area (Li et al., 2013; Liu et al., 2013c; Sun et al., 2006; Yang et al., 2003). In the NCP, winter wheat is irrigated three to five times depending on seasonal rainfall situations (Binder et al., 2007; Zhang et al., 2002). In order to reduce irrigation in winter wheat, knowledge about crop responses to water stress during different growth stages may lead to practical implications for irrigation scheduling (English and Nakamura, 1989; Ghahraman and Sepaskhah, 1997).Winter wheat is not sensitive to water stress at the early growth stage (Zhang et al., 1999). Its response to water stress at different growing stage with the period from stem elongation to milking being particularly sensitive to water stress (Li, 1990). Thus it is essential to develop the most suitable irrigation practice scheme which can guide to use suitable irrigation water application method with proper irrigation scheduling in order to produce optimum crop yield under limited water supplies.

Yield increases in intensive farming practices mostly depend on the timely and adequate application of required irrigation water(Ertek et al., 2006). Many researchers had found large seasonal variation in winter wheat yield under rain-fed condition because of seasonal variation in rainfall and its distribution. Chen et al. (2014), had reported that the seasonal variation in yield was much reduced when winter wheat was well irrigated. He found that the average yield increase was 1593.7 kg ha^{-1}, 343.4 kg ha^{-1}, 116.7 kg ha^{-1}, 82.9 kg ha^{-1}, and 26.2 kg ha^{-1} by adding one more irrigation from rain-fed up to 4 times, respectively, during the five season. He also recommended that moderate irrigation (one or two irrigation application) for the purpose of relative higher grain yield in NCP. The time of irrigations, relative to stage of growth, may be an important factor in crop yields but it is difficult to completely divorce the effects of timing from the effects of frequency (English and Nakamura, 1989). He had mentioned that the high frequency irrigation did not increase yields under full irrigation, nor it mitigate the effects of deficit irrigation and found highest yields with a relatively long irrigation interval of two weeks.

The experimental result by Wang et al. (2012) has shown significant effects on crop growth and grain yield of winter wheat under drip irrigation and level-basin irrigation with different irrigation level. Liu et al. (2011a), shown that leaf area index (LAI) of winter wheat was higher and active leaf area lasts a longer time in sprinkler irrigation than in surface flooding. Biomass of winter wheat at harvest date is 4% ~ 22.1% higher in sprinkler irrigated than in surface irrigated fields. Similarly, the yield is higher by 11.5% ~ 50.9 % due to higher test weight (1000 kernels weight) in the sprinkler irrigated field. Liu et al. (2011b) also concluded from his experiment on winter wheat with sprinkler irrigation that LAI, dry biomass, 1000-grains weight and yield were negatively affected by water stress with irrigation depth (including rainfall) less than 0.5E (E is the net evaporation). He further explained that, while irrigating with a depth over 1.0E also had negative effect on 1000-grains weight and yield. Wang et al. (2012), found significant effect on crop growth and winter wheat yield while comparing drip and basin irrigation with different level of irrigation. He indicated that LAI, plant heights and grain yield had significantly influenced by irrigation amount. Ragheb et al. (2011), found significantly increasing plant height, spike length as well as straw, spikes and total dry weight by increasing irrigation amount water in surface drip irrigation. The analyzed result by Wang et al. (2013) showed that irrigation amount in SDI mainly affects grains per spike and test weight.Noreldin et al. (2015) wrote that the accumulation of above ground biomass and grain yield under drip irrigation will be higher, compared with it under sprinkler irrigation and can achieved at low water stress index.

Lu and Fan (2013), simulate wheat potential yields with EPIC using daily weather data from 1960 to 2007 at 43 representative sites varied from 6.6 to 9.1 t ha^{-1} in the NCP, generally increasing from north to south associated with decreasing low temperature stress. For the entire region, the weighted average actual yield was 5.7 t ha^{-1}, while the yield gap was 2.7 t ha^{-1}or 32% of the potential yield. Several such research had shown that there is possibilities to increase the winter wheat yield, where irrigation water management is one of the important and necessary attempt to achieve it and make the agricultural sustainable in the NCP. The objective of this study were to compare the effects of different irrigation water application method with different irrigation scheduling on growth and development of winter wheat in order to achieve optimum grain yield with minimum irrigation water. The results could provide references for NCP farmers and irrigation researcher in managing winter wheat by deciding proper irrigation schedule depending on weather condition, soil characteristics and available irrigation water application method.

6.2 Methodology

6.2.1 Plant sampling to study crop physiology

The plants samples were randomly selected from the base not from the top or spike to ensure less bias against selection. Selection of quadrates or rows for sampling were determined randomly by predetermined steps (pacing) from one fixed corner and then placed the quadrate or rows without visual assessment (closed eyes while selecting the sampling spot). The selected sample, quadrate, rows however may at time rejected if it is very obviously not representative of the field or plot. Borders are eliminating either for destructive or non-destructive plant sampling. Consecutive destructive sampling were begin at one end of the subplots (excluding border) from the first date and move steadily down the plot date by date, leaving an adequate buffer area (40-60 cm) between adjacent positions (Bell and Fischer, 1994).

6.2.2 Crop growth and development measurement

Crop growth is the enlargement of an existing organ (e.g., Plant height, expansion of leaf etc), whereas crop development refers to the timing of key events in the morphogenesis of the crop. The following growth and development stages were measured;

i. **Tillers: -**Tillers are normally counted when they are visible above the ligules of the leaf in which they are formed. Every week number of tillers per meter was counted from the fixed selected 1 m row length sample from re-green to flowering stage. For each treatment 3 replication sample of 1 m row length were fixed as described in section 6.2.1.

ii. **Plant Density: -** After knowing the average number of tillers per meter the plant density was calculated by following equations

$$Plant\ Density\ or\ \left(\frac{plants}{m^2}\right) = tillers\ per\ meter \times \frac{100}{d} \tag{6.1}$$

Where, d is the row to row spacing of crop in cm (here, d = 20 cm)

iii. **Plant height (PH): -**It measured from the ground to the average top of the terminal spikelet (not include the awns) or tip of the leaf. Crops pulled up to the vertical position if they are lodged before measurement.

iv. **Above ground biomass: -**After knowing the plant density, above ground biomass per plot was calculated by sampling 15 plants at random. Three replications for each treatment were carried out on weekly basis. The plant materials was dried at 70^{o}C for 24 hr and then weighted (Bell and Fischer, 1994; Tavakoli et al., 2014). The calculation made as fallows;

$$Vegetative\ Biomass\ \left(\frac{g}{m^2}\right) = \frac{weight\ of\ n\ plants\ (g) \times plants\ /m^2}{n} \tag{6.2}$$

v. **Underground biomass: -** The root biomass as underground biomass has described in chapter 5, section 5.2.4.

vi. **Leaf Area Index (LAI): -**The LAI was measured from the destructive plant sample. The plant pulled (uprooted) or dug out of the ground for the above ground dry mass were used to determine the LAI. Leaf length (L) and the greatest leaf width (W) of all 15 sampled plants considered for biomass were measured with ruler. LAI was calculated according to the equations described in Gao et al. (2010), as fallows;

$$Leaf\ area\ per\ plant\ (a) = \frac{\sum_1^n (L\times W)}{n} \times 0.80 \qquad (6.3)$$

$$LAI\ = \frac{a\times N}{S\times 100} \qquad (6.4)$$

Where, n is the number of plant sample consider for leaf area measurement (here n =15), L and W was measured in cm to get leaf area per plant (a) in cm^2, N is the number of plants (tillers) per meter row length, and S is the crops row to row spacing in cm (here S = 20 cm).

6.2.3 Harvesting

Before the irrigation treatment started quadrate samplings were made as described in section 6.2.1. In each treatment three quadrates (3 replications) of 2 m^2 were selected and kept undisturbed till harvesting by fixing four plastic pipe (ϕ =12 mm) pegs and tiding it with clearly visible color plastic rope as shown in fig 2.10. The harvested crop of 1 m^2 from the middle part of these 2 m^2pre-selected quadrate sample were carefully collected into the netted bag as shown in fig 6.1 to study grain yield, straw yield, effective tillers etc.

6.2.4 Post harvest study

Predetermined 1 m crop row length before the irrigation treatment started were harvested, and carefully wrapped in new paper so that no grain or plants will damage (Fig 6.1). The post harvest parameters such as, panicle length, no of spike per panicle, no of grain per panicle etc were studied from 10 randomly selected plants from this 1 m sample. On the other hand the effective and non effective tillers where counted from 1 m^2 crop sample (section 6.2.3) by detecting the number filled ear-head (panicle) and unfilled ear-head (panicle) respectively before threshing the sample.

Figure 6.1 Harvesting, threshing and sun drying for grain yield and post harvest measurement

6.2.5 Threshing and drying

Threshing as well as winnowing of harvested crop was done manually and then the clean grain were put for sun drying (Fig 6.1) until the grain moisture reached to 12 % (Gao et al., 2014; Jin et al., 2009; Lv et al., 2013b).

6.2.6 Grain and straw yield

The separately dried clean grain and above ground straw of 1 m^2 was weight to calculate the grain yield and straw yield per hectare. The test weight of 1000 grain was taken simultaneously from the same bulk mass taken for grain yield per hectare at 12% grain water content. The test weight was taken by 4 decimal precise electronic balances, whereas the bulk grain was weighted by simple electronic balance.

6.2.7 Harvest index (HI)

The term "Harvest Index" (HI) is used in agriculture to quantify the yield of a crop versus the total amount of biomass that has been produced (Munns et al., 2010; Xue et al., 2003). Thus it can be applied as

$$Harvest\ Index\ (HI) = \frac{Crop\ Yield\ \left(\frac{t}{ha}\right)}{Biomass\ \left(\frac{t}{ha}\right)} \qquad (7.5)$$

Where, the crop biomass is the total shoots plus roots dry mass but to compare the results of others similar research the shoot dry mass was only considered for the calculations.

6.3 Effects of Irrigation Method and Scheduling on Crop Physiology

6.3.1 Number of tillers

The weekly measured tillers per meter row length are shown in fig 6.2. It has found that the irrigating winter wheat at 70% and 60% with FI produce effectively more tillers followed by SDI and SI respective whereas irrigating at 50 with SI produce more tillers followed by FI treatment while comparing three irrigation water application method. On the other hand, while studying the individual water application method it reviled that irrigating at 50% with SI and 60% or 70% with SDI produce greater number of tillers per meter length. Irrigating FI at 50% and SI or SDI at 70% of FC has drastically reduced the tillers number. This maybe because such treatments get favorable soil aeration and irrigation amount was sufficient for vegetative growth.

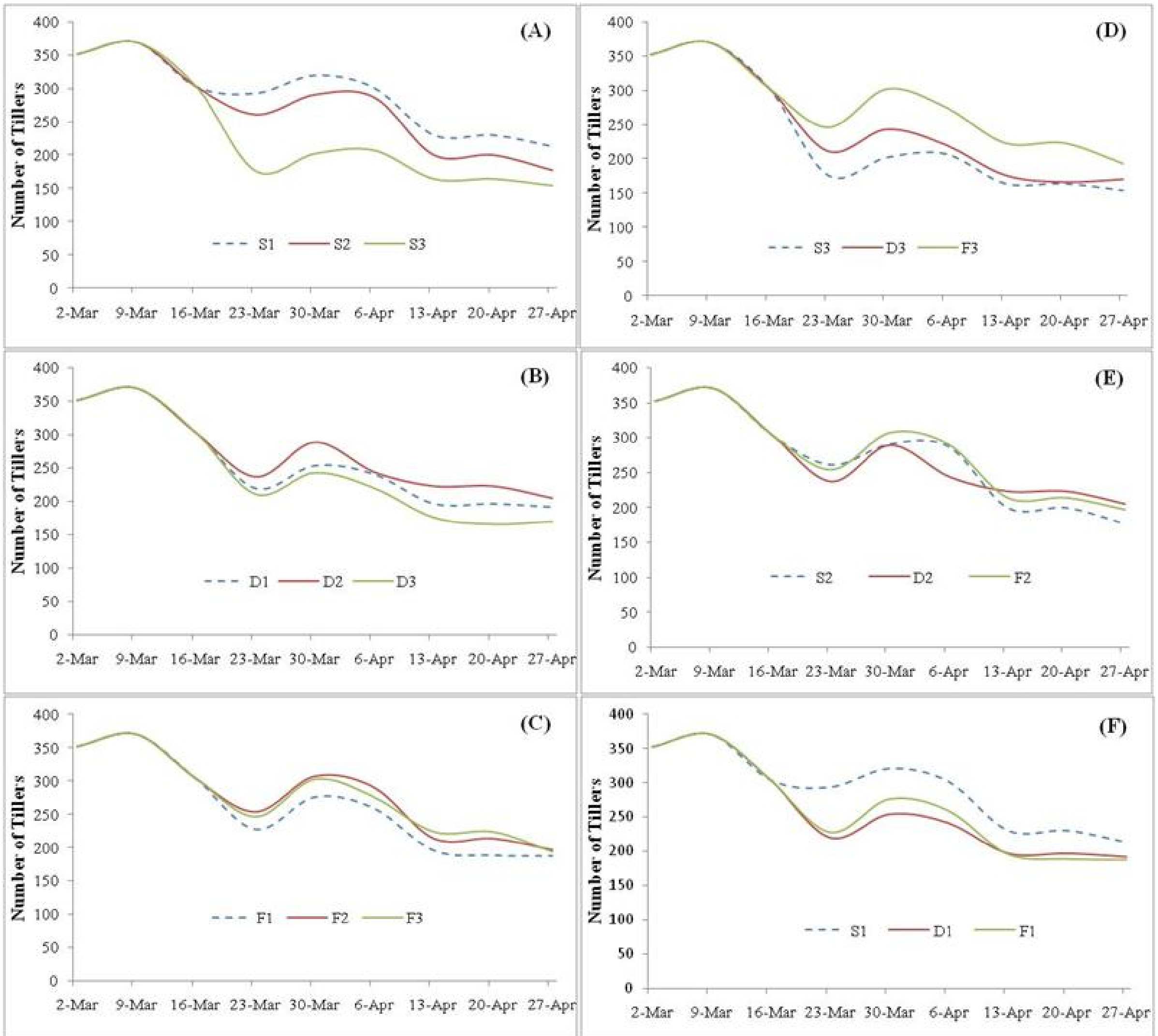


Figure 6.2 **Number of tillers per meter row crop length in SI (a), SDI (b), FI (c) and in 70% (d), 60% (e), and 50% (f) of FC**

6.3.2 Crop height

The weekly measured crop height during crop growth stage from mid-March to mid of May is presented in fig 6.3. The crop grew faster with higher irrigation scheduling treatment (70% IST) and the growth rate was retarded for low irrigation scheduling (50% IST) but finally all treatment attained average non-significant maximum height. Only the treatments F1 achieve significantly lowest height and other all treatment gains the average maximum crop height. In all irrigation scheduling, the SI treatment gives highest crop height followed by FI whereas, SDI achieve relatively lower crop height except at 50% irrigation scheduling treatment (Table 6.1). The maximum height attained by S3 is 71.15 cm followed by 70.95 and 70.75 cm in F3 and D3 respectively at 70% IST whereas the lowest crop height in F1 (68.67 cm) followed by D1 (69.05 cm). Irrigating at 60% of FC will give relatively lower crop height than at 70% but was not found significant.Wang et al. (2012), when compare plant height (PH) for level-basin irrigation (BI) and drip irrigation (DI) he found highest PH in BI at high level of irrigation scheduling while the PH was higher in DI at low irrigation scheduling treatment at final growth stage of winter wheat.

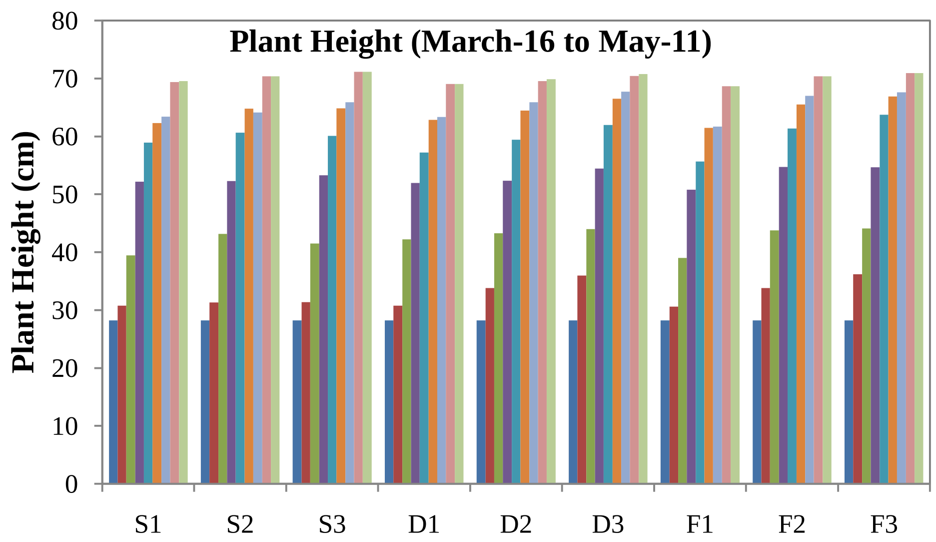


Figure 6.3 Crop height measured every week from re-green to maximum height reached

6.3.3 Leaf area index(LAI)

The leaf area index (LAI) measured every week from turn green to grain filling stage is presented in fig 6.4. All treatments reached a maximum value for LAI in the steam-elongation stage on April 06, 2015 (171 DAS) and then decreased with crop growth approaching the heading to maturity phase. It has found that the high (70% of FC) irrigation scheduling treatments (IST) produce more leaf area index than the low IST 60% and 50% respectively in all irrigation method (Wang et al., 2012). Comparing the irrigation water application method for LAI under similar irrigation scheduling it has seen highest LAI for FI and lowest for SI at 70% IST, and similar LAI pattern was found at 60% IST and 50% IST. The field experiment with sprinkler irrigation on winter wheat at NCP by Liu et al. (2011b) had shown that irrigation depth lower than 0.50E (50% of evaporation) gives negative effects on LAI. This proves the LAI in S3 greater than S2 and S1 is the coincident results with Liu et al. (2011b). The result presented by Kharrou et al. (2011) is different than the result of this study, where he had found higher LAI for drip irrigation than full irrigated flood irrigation.

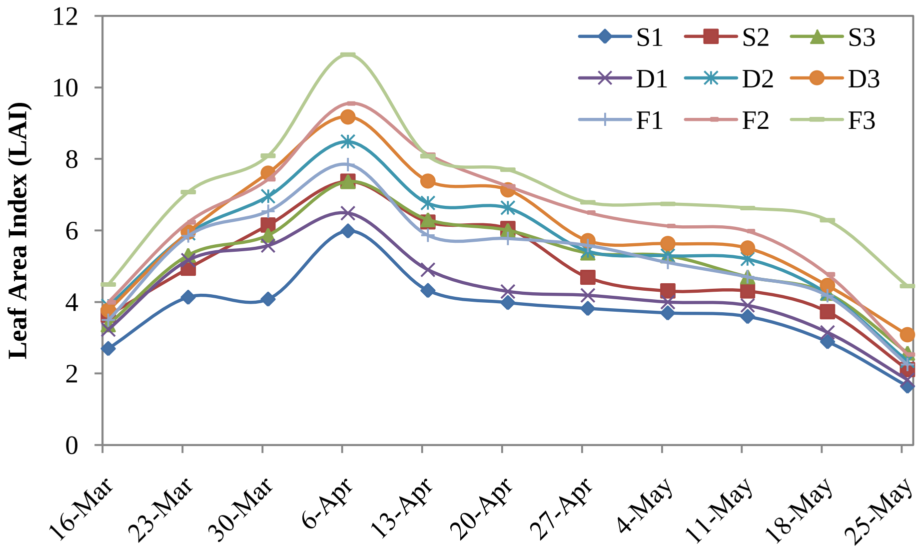


Figure 6.4 **Weekly measured Leaf Area Index (LAI)**

6.3.4 Shoot biomass

Above ground crop dry mass accumulation (shoot biomass), measured weekly are presented in fig 6.5. It has clearly seen that the high irrigation frequency treatment produce relatively more shoot biomass than the low irrigation treatments while comparing irrigation level for individual irrigation method. This results is similar to the result of Li et al. (2013) and Liu et al. (2011b). In general, at 70% irrigation level, SI produced more biomass followed by SDI during revival, at 60% and 50% irrigation level, SDI produce more biomass followed by FI. Likewise, from jointing to anthesis with 70% and 60% irrigation, FI produce more biomass followed by SDI and SI respectively but with 50% irrigation scheduling SI produce more followed by SDI and lowest in FI maybe because of water stress developed in FI at this growth stage. After anthesis to maturity SDI produce more biomass followed by SI and FI at 70% and 60% respectively, whereas at 50% irrigation scheduling FI produce more biomass compare to SDI and SI because, FI received more irrigation water at this stage. The consistency not found with individual irrigation method in producing biomass at different growth stage within same level of irrigation was maybe because of irrigation interval and amount of irrigation water. The treatments SDI and SI as shown in fig 6.5a and 6.5b are similar pattern presented by Noreldin et al. (2015).

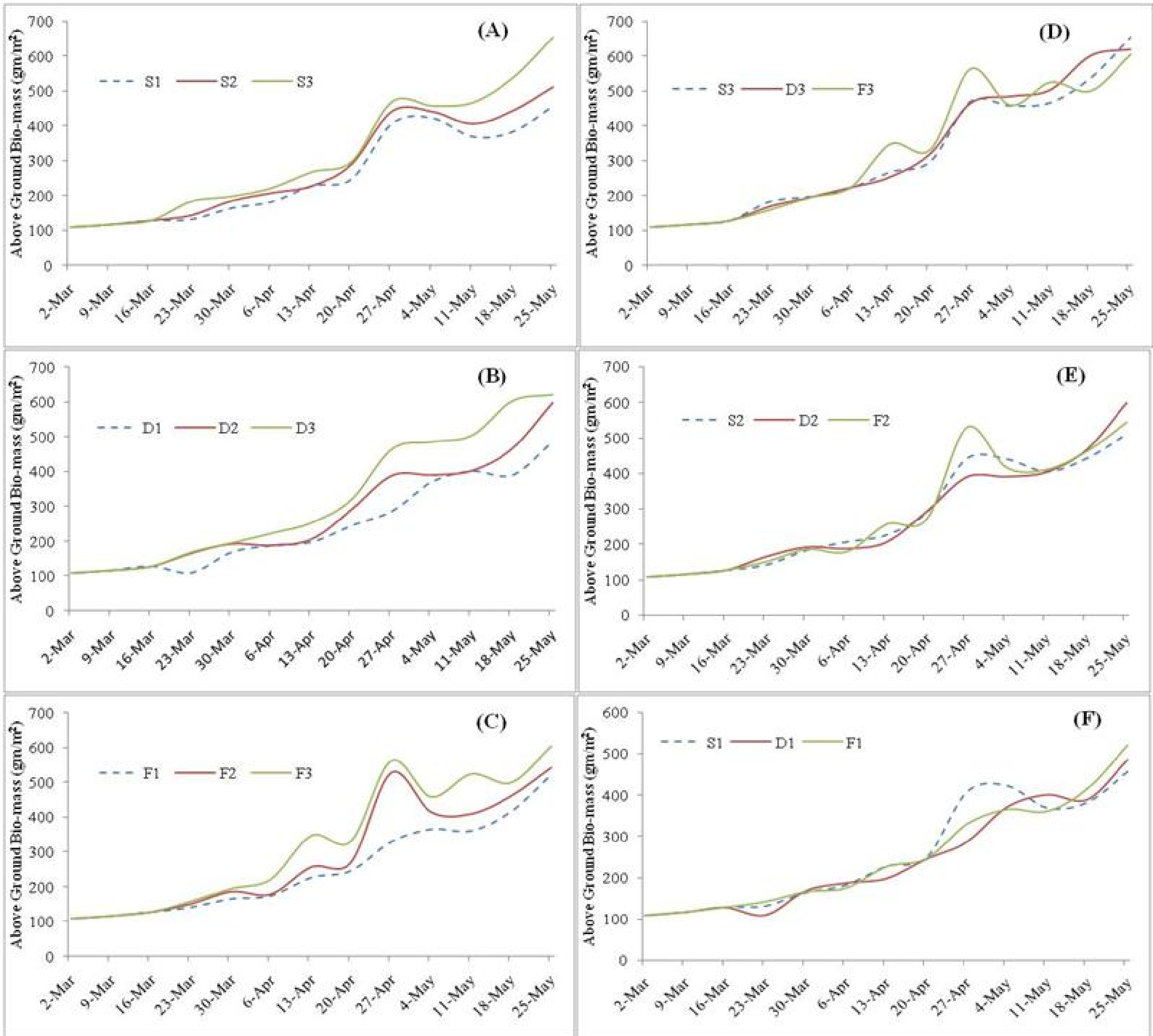


Figure 6.5 **Comparison of above ground shoots dry biomass in different irrigation method (a, b, c) and under different irrigation scheduling (d, e, f)**

6.4 Effects of Irrigation Method and Scheduling on Crop Harvest

6.4.1 Effective and non effective tillers per square meter

The effective tillers and non-effective tillers measured at harvesting from same 1 m^2 harvest sample taken for grain yield measurement, is presented in table 6.1. The effective tillers considered if earheads contains filled spikes, has found significantly (α =0.05) different for irrigation method and are highly significant (α =0.01) for irrigation scheduling. The higher number of effective tillers in D2 was found 774 followed by F2 (754) and was lowest number in F1 (681) followed by S1 (708). This shows irrigating at 60% of FC produce relatively higher effective tillers than excessively irrigated (70% IST) and reduce drastically in the water stressed treatment (50% IST) under same irrigation method. While, under the same irrigation level SDI produce more tillers followed by FI and lowest in SI treatments. The highest no of effective tillers found in at 60% maybe because of high soil temperature and favorable soil water content than 70% IST, whereas at 50% even the soil temperature was higher the effective tillers reduced because of soil water stress. The similar statement has found in WEI and LI (2001) field research study for dryland spring wheat. The adverse result has found for non-effective tillers and analysis shows non-significant at α =0.05 with irrigation method but significant (α =0.05) with irrigation scheduling. Obviously, number of non effective tillers has found highest in less frequent (50%) irrigation treatment F1 (20) followed by S1 (13) and lowest in D2 (7) followed by F2 (9). Only 50% IST has found significant with 60% and 70% IST under FI other irrigation relatively produce relatively similar same number of non effective tillers.

6.4.2 Panicle length

The mean panicle length of 10 randomly selected plants from the 1 m crop row length harvested sample (section 6.2.4) is given in table 6.1. The study shows that the length of the panicle is significantly different in SDI at 50% (i.e. treatment D1) with 60% and 70% of FC. In other irrigation method SI and FI the length of panicle was not found significant with irrigation level. All irrigation method under the same level of irrigation scheduling also not found significant maybe due to the varietal characteristics of crop genotype. But the irrigation level has reduced the length to some extent in water stress treatment. The highest panicle length was found in D2 (7.52 cm) followed by D3 (7.47 cm) and S2 (7.38 cm) whereas the smallest length was measured for D1 (6.80 cm) followed by S1 (6.99 cm).

6.4.3 Flag leaf dry mass

The dry weight of flag leaf taken from 100 randomly selected flag leaf from each treatment with three replications found non- significant with irrigation method or with irrigation scheduling. Although, the results was not significant, the treatments irrigated frequently (70% of FC) produce greater weight than low irrigated treatments for all individual irrigation method, which shows the consistent results given by Zhang et al. (1998). While comparing different irrigation method, the FI gives more dry weight followed by SDI.

Table 6.1 **Grain yield and post harvest yield potential components**

Treatments	Grain Yield (t/ha)	1000 Kernel Weight (gm)	Straw Yield (t/ha)	Effective Tillers per m^2	Non-Effective Tillers per m^2	Wt. of 100 Flag Leaf (gm)	Maximum Plant Height (cm)	Panicle Length (cm)	Per Panicle			Harvest Index (%)
									Filled Spikelets	Unfilled Spikelets	Number of Kernel	
S1	8.44^{d}	43.54^{d}	7.82^{bc}	708^{de}	67^{ab}	9.57	69.555^{a}	6.99^{ab}	16.17^{cd}	2.3^{a}	32.37^{bc}	51.9^{ab}
S2	9.21^{abc}	47.77^{abc}	8.14^{b}	746^{abc}	53^{b}	9.61	70.395^{a}	7.38^{a}	16.8^{abc}	1.87^{a}	34.43^{ab}	53.07^{a}
S3	9.13^{bc}	48.73^{abc}	8.68^{ab}	721^{cd}	58^{b}	10.05	71.145^{a}	7.35^{ab}	16.77^{abc}	1.9^{a}	33.73^{b}	51.68^{ab}
D1	8.28^{d}	45.06^{cd}	7.26^{c}	720^{cd}	65^{ab}	9.91	69.05^{a}	6.8^{b}	16.1^{cd}	2.3^{a}	31.57^{c}	53.28^{a}
D2	9.53^{a}	49.89^{a}	8.28^{b}	774^{a}	37^{b}	11.71	69.86^{a}	7.52^{a}	17^{ab}	1.8^{b}	36.13^{a}	53.58^{a}
D3	9.37^{ab}	49.55^{ab}	8.33^{b}	743^{abc}	60^{ab}	10.13	70.75^{a}	7.47^{a}	17.27^{a}	1.87^{a}	34.2^{ab}	52.93^{a}
F1	8.26^{d}	45.14^{cd}	8.04^{bc}	681^{e}	98^{a}	10.45	68.665^{b}	7.13^{ab}	15.9^{d}	2.33^{a}	31.13^{c}	50.71^{bc}
F2	9.07^{bc}	45.73^{bcd}	8.38^{b}	754^{ab}	43^{b}	10.83	70.39^{a}	7.29^{ab}	16.33^{bcd}	1.97^{a}	33.23^{bc}	51.97^{ab}
F3	8.99^{c}	46.83^{abcd}	9.23^{a}	730^{bcd}	58^{b}	10.97	70.95^{a}	7.18^{ab}	16.33^{bcd}	2.07^{a}	32.53^{bc}	49.34^{c}
LSD (0.05)	0.34	3.99	0.81	32.02	7.83	1.61	2.43	0.57	0.79	0.52	2.10	2.12
Irrigation Method	*	ns	*	*	ns	ns	ns	ns	*	ns	*	**
Irrigation Scheduling	**	**	**	**	*	ns	*	*	**	*	**	*

* Significant Level at 5% (α =0.05)
** Significant Level at 1% (α =0.01)
ns Non-Significant at 5% (α =0.05)

6.4.4 Number of filled and unfilled spikes per panicle

Numbers of filled and unfilled spikes per panicle was the measure of the mean of 10 randomly selected plants from 1 m row length harvested sample (section 6.2.4) and are presented in table 6.1. The ANOVA shows only SDI significantly (α =0.05) increased filled spikes per panicle compared to FI but non-significant with SI and irrigation methods have no effects on unfilled spikes per panicle. Whereas irrigation scheduling influenced filled spikes highly at α =0.01 level of significant and shows significant effects (α =0.05) on unfilled spikes in SDI system but in case of SI and FI treatments irrigation level didn't shows significant different either for filled or unfilled spikes formation. Although, higher number of filled spikes was found at 60% followed by 70% in SI and FI treatments. The deficit irrigation increases unfilled spikes in all irrigation method and reduces the numbers for increasing frequency. The highest number of filled spike has found in D3 (17.27) followed by D2 (17.0) and lowest in F1 (15.90) followed by D1 (16.10) likewise in reverse way, highest number of unfilled spikes was found in F1 (2.33) followed by S1 (2.3) and lowest number in D2 (1.8) followed by D3 (1.87)

6.4.5 Number of kernel per panicle

Number of kernel per ear head (panicle) has found significant (α =0.05) with irrigation method and highly significant (α =0.05) for irrigation scheduling (Table 6.1). The highest 36.13 kernels per panicle was found in SDI at 60% (D2) followed by S2 (34.43) and lowest 31.13 kernels in FI at 50% (F1) followed by D1 (31.57). The result shows that the winter wheat produces higher number of kernel while scheduling at 60% of FC with SDI followed by SI method and kernel number reduced significantly either irrigated more or in water deficit condition. Liu et al. (2011b), receive 33.21 and 32.63 kernels while irrigating 0.625E and 0.75E (E is surface evaporation) under sprinkler irrigation in 2008 and 2006 respectively and the found less kernels either irrigating more or creating water stress than corresponding irrigation levels. The analyzed result by Wang et al. (2013) showed that irrigation amount in surface drip irrigation mainly affects grains per spike and test weight and has proved consistent with this study.

6.4.6 Kernel weight

The kernel weight measured from 1000 kernels weight (test weight) is presented in the table 6.1. The test weight of winter wheat also found non-significant with irrigation method but found highly significant (α =0.01) with irrigation scheduling in case of SDI and SI treatments. This shows that SDI and SI have capacity to increase the test weight under suitable irrigation scheduling. The test weight, which is one of the most critical parameter in determining the grain yield, had found less in water stress condition in either irrigation method. The highest test weight of 49.89 g has found in D2 treatment followed by D3 (49.55 g) and S3 (48.73 g) respectively and lowest in S1 (43.54 g) followed by D1 (45.06 g) treatments. The results obtained concede with Liu et al. (2011b) where he found similar higher 1000 grain weight of 50.04 g in most irrigated treatment under sprinkler irrigation and the weight has decreased with decreasing number of irrigation.

6.4.7 Grain yield

The most important parameter of this study was to increase the grain yield (GY) per unit volume of irrigation water applied. The result obtained for grain yield (in ton per hectare), calculated from 1 m^2 harvest of each treatment is presented in table 6.1. The analysis of variance (ANOVA) shows that, irrigating winter wheat with different irrigation method had significantly (α=0.05) influenced the grain yield and highly significant (α=0.01) with different level of irrigation scheduling. The yield data received in this study varied from 9.53 t/ha to 8.26 t/ha supports the simulated potential yield of Lu and Fan (2013), where he had found potential yield of winter wheat 9.1 t/ha for NCP. He further illustrated that the yield gap 2.7 t/ha of the potential yield can be obtained by proper irrigation management. This study found maximum level of grain yield in D2 (9.53 t/ha) followed by D3 (9.37 t/ha) and S2 (9.21 t/ha). The yield in SDI treatments was found significantly higher than FI treatment but not significant with SI treatments at 70% and 60% irrigation level whereas SI and FI was also not significant at those irrigation levels. All irrigation method with 50% scheduling produced soil water stressed and hence reduced GY drastically but was not significant between irrigation methods whereas S1 (8.44 t/ha) performed better than D1 (8.28 t/ha) and F1 (8.26 t/ha). Even the kernel weight at 70% in SI and FI is more than 60% the grain yield per hectare found more in 60% than in 70% for all irrigation method because of more effective tillers, and large number of grain per panicle at 60% IST than 70% IST .Zhang et al. (2010), also concluded that maximum grain yield production was achieved with moderate water deficit whereas, Noreldin et al. (2015) found more grain yield in drip irrigation than sprinkler irrigation even at same level of irrigation scheduling. The higher grain yield in SI than in FI for this study is certified with the results obtained by Liu et al. (2011a). The higher grain yield in SDI and SI is because of higher kernel weight for in the corresponding irrigation method.

6.4.8 Straw yield

The straw yield measured from the harvested sample of 1 m^2 is presented in table 6.1 shows that irrigation method and irrigation scheduling both significantly affects the straw yield. The analysis shows FI treatment significantly produce higher straw yield than SI and

SDI and found more biomass at highly irrigated treatment whereas SI and SDI shows non-significant result at all level of irrigation. The maximum straw yield was found in F3 (9.23 t/ha) followed by S3 (8.67 t/ha) and lowest in D1 (7.26 t/ha) followed by S1 (7.82 t/ha). More straw yield in FI treatment maybe because at 1st irrigation after turn green it irrigated with 60 mm per irrigation while SI and SDI irrigated with 30 mm which leads more vegetative growth in early stage. Similarly, at 70% and 50% SI received more frequent irrigation than SDI at vegetative but at 60% both receive nearly same frequent irrigation this makes higher vegetative growth in S3 and S1 than D3 and D1 respectively and straw yield lead in D2 compare to S2. Noreldin et al. (2015), shows higher accumulation of above ground biomass under drip compare than sprinkler which seems true for 60% irrigation treatment but at 70% and 50% this study result shows higher straw yield in SI than in SDI. Under North China Plain conditions increased above ground biomass was the most important factor leading to higher yield. The straw yield in 70% IST found more because of after heading, the above ground biomass continued to accumulate and in most case reached the highest value at harvest (Zhang et al., 2008b).

6.4.9 Harvest index (HI)

The harvest index (HI), which considered as the ratio of grain yield to the above ground straw yield was varied from 53.58% in D2 followed by D1 (53.28) to the lowest of 49.34% in F3 (Table 6.1). Munns et al. (2010), had mentioned the highest HI for wheat as 0.55, which verify this experimental result. The ANOVA shows that HI has significantly affected by irrigation method and irrigation scheduling. It has been analyzed that irrigating with FI either at 50% or 70% of FC will cause to reduce HI significantly. The reason for this maybe because of lowest grain yield and biomass in F1 whereas, F3 produce highest biomass but didn’t increased grain yield in the same ratio. The reason for lower HI in S3 has found similar to F3. In an overall, all irrigation method had found satisfactory HI at 60% of FC leaded by SDI treatment whereas FI proved worst when irrigated at 70% and 50% of FC. The result for HI under 50% IST and 60% IST in this study was found consistence with Zhang et al. (2010) but not maintain similar pattern in 70% IST where he had explained that under less irrigated condition HI increased 2-4% more than more irrigated conditions.

6.5 Conclusion

The results showed that irrigation method and irrigation scheduling both significantly influenced the crop growth and yield of winter wheat. Chapter include the study of plant height, dry matter accumulation, plant/m^2, tiller/plant, number of spikes/m^2, spikelet/spike, grain/spike, 1000-grain weight, grain yield, straw yield, biomass, harvest index. It has found that Plant height, leaf area index, dry biomass, grain per panicle, test weight, and grain yield were negatively affected by water stress. The treatment scheduling with FI increase vegetative growth but reduce yield parameters like effective tillers, length of panicle, grains per panicle, filled spike per panicle test weight and hence finally grain yield. The maximum grain yield of 9.53 t/ha obtained in SDI irrigating at 60% of FC followed by 9.37 t/ha with same irrigation method at 70% irrigation scheduling provide an evidence that SDI have potential to achieve optimum grain yield for proper irrigation water management. Irrigating at 60% of FC with SDI not only increase grain yield but also gain highest harvest index (53.58%), effective tillers/m^2 (774), panicle length (7.52 cm), grains per panicle (36.13), 100 flag leaf weight (11.71 gm), and 1000 grain weight (49.89 gm).

Irrigating winter wheat at 70% of FC comparatively encourages vegetative growth and hence attained higher crop height, LAI, dry biomass and produced more straw yield. The low irrigation scheduling treatment get stressed at either crop development stages. At every level of irrigation SDI and SI can perform better than FI because of higher no of irrigation which allows maximum utilization of irrigation water and reduce the duration of water stress in the upper root zone where maximum root found exist. Similarly irrigating at 60%, neither allowed soil to become dry for longer nor it make unfavorable soil-water environment and keep soil aeration. This will help winter wheat to regain all crop development stages as per their genetic characteristic and hence significantly increase effective tillers per meter square, panicle length, filled spike per panicle, kernel number per panicle, test weight as well as grain yield and harvest index. The irrigation water applied in FI was higher than SDI and SI but do not found higher yield and yield component at any level of irrigation. On the other hand, number of irrigation and total irrigation water applied were obviously more at 70% irrigation level but most of the yield parameter found higher at 60% IST and also produce highest grain yield. These results indicate that excessive irrigation might not produce greater yield or optimal economic benefits, thus suitable irrigation scheduling with appropriate irrigation method should be established.

Chapter 7 Irrigation System Evaluation

7.1 Introduction

More than 70% of fresh water is used in agriculture in many part of the world (Du et al., 2015) thus for future global food security, water use in agriculture must become sustainable. Improving agricultural water use efficiency (WUE) is a strategic requirement for food security. Agricultural water-use efficiency can be improved at different points. A promising approach is the use of deficit irrigation and efficient irrigation method, which can both save water and induce plant physiological regulations such as reproductive and vegetative growth. According to a survey conducted by “Ministry of Water Resources”, if the irrigation water effective use ration improve from 0.5 to 0.7, approximately 60-70 billion m^3 of water would be saved; and even if the irrigation water productivity increased only from 1.1 to 1.5 $kg.m^{-3}$, about 100 billion m^3 of water would be saved to produce the same cereal yield (Du et al., 2015). The WUE generally found increasing if the crop yield will increase. Hence one of the key options to increase WUE is to increase crop yield.

Engineers as well as agronomists use the term “irrigation efficiency”. For the irrigation scheme, the amount of water stored in the root zone is related to the amount of water delivered for irrigation. For agronomists, there are various definitions of irrigation efficiency. Basically, efficiency relates the agricultural yield to water consumption (Blumling et al., 2007). It is defined as the ratio of the crop yield to the water consumed to produce the yield, that is, evapotranspiration or, better, transpiration (Hatfield et al., 2001; Kang et al., 2002; Li et al., 2013; Wang et al., 2013; Zhang et al., 2004b).

$$Water\ Use\ Efficiency = \frac{Yield}{(E)T} \tag{7.1}$$

Water use efficiency varies with crop species, available energy from sunlight, atmospheric pressure, etc. and hence expresses as the properties of a plant at a certain location, that is, the characteristics of a crop. To specify the above “Water Use Efficiency” in order to take the benefits of irrigation into account, “Irrigation Water Use Efficiency” seems to be more suitable from an agronomic perspective (Howell, 2001). He calculated it by first subtracting the yield which would be achieved without irrigation from the yield which is produced with the help of irrigation. The same applies for the water fraction in the denominator where evapotranspiration of the precipitation input during the growing season is subtracted from evapotranspiration of irrigation water input.

$$Irrigation\ Water\ Use\ Efficiency = \frac{Yield_{with\ irrigation} - Yield_{without\ irrigation}}{ET_{irrigatated\ \ field} - ET_{Rainfed\ \ field}} \tag{7.2}$$

This definition of irrigation efficiency incorporates agronomic aspects of plant characteristics as well as the management of irrigation. The Irrigation costs, crop yields, and irrigation efficiencies may all be affected by frequency and method with which water is applied and can also have economic implications importance. Chen (2014) has found that, the benefit of increasing irrigation number was significantly reduced with the further increase in irrigation. He concluded that WUE decreased with the increase in irrigation and recommended that moderate irrigation (1~2flood irrigation) was recommended in NCP region for the purpose of relative higher WUE.Liu et al. (2013c), also found decreasing WUE with increasing irrigation in his 4 years winter wheat experiment at NCP. English and Nakamura (1989), found highest WUE for wheat while irrigating at intervals of 4 weeks.

In North China, the irrigation water to meet crop water requirement for winter wheat can't be ignore as explained in chapter 1. The amount of irrigation water required depends on rainfall and the efficiency of the irrigation system (Ottman et al., 2012). Since sprinkler irrigation has the potential for improving water use efficiency and grain yields, it is increasingly being used in NCP (Liu and Kang, 2006b). Center pivots with modern sprinkler packages can be highly efficient in terms of uniformity and application efficiency (Schneider, 2000), as can SDI (Camp, 1998), and numerous studies have documented high crop productivity using either type of system. Liu et al. (2013a), has mention through his experimental results that water productivity (WP) was higher by 18~57% and irrigation water productivity (IWP) was higher by 21~81% in the sprinkler field than in surface irrigated field. Study of winter wheat by Yang et al. (2000) shows higher crop yield and water use efficiency in sprinkler irrigated field than that in surface irrigated fields.Noreldin et al. (2015), used Crop Syst (Cropping System Simulation), as analytic tool to analyze the relationship between applied irrigation and the resulted yield under sprinkler and drip irrigation. He found that using 100% ETc under drip system resulted in very low water stress index (WSI =0.008), whereas using 100% ETc sprinkler system resulted in WSI =0.1. Rahman (2009), mentioned that drip irrigation has become more popular for several crops. Drip irrigation is an efficient method for minimizing the water used in agricultural and horticultural crops. But it is well known that these methods can result in water saving if the correct management procedures are applied (Darusman et al., 1997).

Many studies have been carried out to find the best ways for efficient use of irrigation water and improve crop yield (Zhang et al., 2010). Plant WUE depends on the quantities applied and timing. Improving irrigation efficiency by applying deficit irrigation is an important management practices, especially in region with serious water shortage. A more frequently irrigated crop might increase soil evaporation, so that with a limited irrigation supply, balancing the irrigation amount per application and irrigation frequency with root water uptake would be expected to affect yield as well as WUE (Lv et al., 2013b).

7.2 Evaluation Approach

7.2.1 Irrigation water utilization

Irrigation systems were evaluated on the basis of irrigation water utilization by crop. It was estimated as water use efficiency (WUE), irrigation water use efficiency (IWUE) and field water use efficiency (FWUE). The WUE, IWUE and FWUE were calculated with the equations 7.3, 7.4 and 7.5 respectively. Even the equation 7.4 does not define the exactly meaning of irrigation water use efficiency but in general the equation has been followed by different researchers as an easy evaluation (Hendawy and Hokam, 2007; Kanber et al., 1993; Li et al., 2013; Ma et al., 2015; Zhang et al., 1999; Zhang et al., 2007).

$$WUE = \left(\frac{Y}{ET_c}\right) \times 100 \quad (7.3)$$

$$IWUE = \left(\frac{Y}{I}\right) \times 100 \quad (7.4)$$

(Hendawy and Hokam, 2007; Ma et al., 2015)

$$FWUE = \left(\frac{Y}{I+R}\right) \times 100 \quad (7.5)$$,(Michael, 1978)

Where, WUE IWUE and FWUE are respectively in $kg.ha^{-1}mm^{-1}$, yield (Y) in $kg.ha^{-1}$, evapotranspiration (ET_c) in mm, applied irrigation water (I) in mm and rainfall (R) in mm. The table 7.1 presents all efficiencies calculated for all irrigation systems.

7.2.2 Inter-relationships

The main goal of water saving irrigation system is to increase WUE/IWUE without decreasing yield. Hence, it is necessary to understand the relationship among grain yield and the factors influencing the grain yield. The approach here considered for the evaluation of different irrigation method with different irrigation scheduling for irrigating winter wheat is the relationship found between different yield parameters and irrigation water utilization. The inter-relationships with co-relation coefficients of the followings are evaluated.

i. Grain yield and Evapotranspiration Vs Irrigation amount
ii. Grain yield and Straw yield Vs Evapotranspiration
iii. Grain yield and RWU
iv. WUE and IWUE Vs Irrigation amount
v. Grain yield Vs WUE
vi. Grain yield Vs IWUE
vii. WUE Vs Harvest index (HI)

7.3 Irrigation Water Utilization

7.3.1 Water use efficiency (WUE)

Water use efficiency (WUE) is calculated as defined in section 7.2.1 and the data were presented in table 7.1. The result shows that the WUE for D2 and S2 was found significantly higher than all treatments whereas, F1, F3, and D1 respectively reduce WUE. Likewise, treatments S1, D3, F2 and S3 were gives satisfactory values of WUE. The highest WUE value of 2.08 kg m^{-3} for D2 followed by S2 (2.05 kg m^{-3})and lowest 1.86 kg m^{-3} for F1 followed by F3 (1.88 kg m^{-3}) shows that the irrigation interval and amount of irrigation per irrigation, which effectively plays role to influence the grain yield will also actively determine the WUE. The WUE obtained for this study was similar to the results obtained by Lv et al. (2013b) and Wang et al. (2015)where they found WUE ranging from 1.70 to 4.20 kg m^{-3} and 1.91 to 2.06 kg m^{-3} respectively. Similarly, Li et al. (2013), receive maximum WUE of 3.3 kg m^{-3} for irrigation 60 mm each at jointing and flowering with surface flooding. Liu et al. (2013c), also obtained similar range of WUE but he consistently receive optimum WUE for minimum irrigation amount and lowest WUE for maximum water application, whereas in this study the treatment F1, D1 and S1 which receive minimum irrigation water drastically reduces the grain yield and hence cause to decrease the overall WUE (Lv et al., 2013b). Likewise, the treatments irrigated with 70% of FC produce more grain than 50% irrigated treatments but influence to occurred more ET than that occurred in 50% treatment, which finally reduce the WUE of 70% irrigation treatments. Thus comparing overall all treatments it reviled that irrigating winter wheat at 60% of FC either by SDI or SI or FI method will give satisfactory higher WUE but SDI has found more effective than SI and FI in receiving the higher WUE. Wang et al. (2012), also found significantly improved grain yield and WUE in drip irrigation (DI) method compared with the level basin (BI) method and obtained higher crop water productivity when soil water was depleted to 60% and 50% of field capacity.

7.3.2 Irrigation water use efficiency (IWUE)

Irrigation water use efficiency (IWUE) of the most irrigated treatments F3, S3, F2, and D3 were the respectively lowest and found highest for low irrigated treatments S1, D1, F1, D2 and S2 respectively in sequence which is consistent result given by Sun et al. (2006). The IWUE in FI (F1, F2 and F3) found significant lower than SI (S1, S2 and S3) and SDI (D1, D2 and D3) at corresponding level of irrigation scheduling, whereas irrigating under SI and SDI does not varied significantly except at 70% IST. Similarly, under same irrigation method IWUE varied with different level of irrigation scheduling. The calculation for IWUE (Table 7.1) results to find increasing IWUE by 36.3%, 21% and 16% for SI as well as 33%, 26% and 39% for SDI compare to FI while irrigating winter wheat at 50%, 60% and 70% of FC respectively. Similarly, irrigation water was saved 25%, 16.7% and 12.5% in SI and 25%, 16.7% and 25% in SDI compare to FI. This shows that both SI and SDI system had significant advantage of improving IWUE under deficit irrigation condition whereas, SDI perform even better than SI under increasing irrigation frequency (Wang et al., 2012). The overall results concluded that irrigating winter wheat with either different irrigation method or at different irrigation scheduling were significantly affects the IWUE at $\alpha = 0.01$significance level (Table 7.1). The values for IWUE vary from 9.38 kg m^{-3} in S1 to 3.75 kg m^{-3} in F3. The higher IWUE at the low levels of irrigation can be attributed to the greater use of rainfall and available soil water (Zhang et al., 1999). In addition, at the high levels of irrigation IWUE decreases because the part of the irrigation water left in soil profile at harvest and deep percolation beyond the root zone and into groundwater (Schneider and Howell, 1997).

7.3.3 Farm water use efficiency (FWUE)

The farm water use efficiency (FWUE) or total (irrigation + Rainfall) water use efficiency depends on the management of irrigation water according to the rainfall pattern. Higher the IWUE, more efficient FWUE can be achieved. The FWUE for this study was hence found highly significant ($\alpha = 0.01$) with irrigation method and irrigation scheduling (Table 7.1). Like IWUE, the FWUE increases with deficit irrigation and decreases with increasing irrigation frequency. The maximum value of FWUE was estimated on S1 (3.70) followed by D1 (3.63) and lowest for F3 (2.38) followed by S3 (2.62). SDI treatments with 60% IST reduce 10.64% and 8.82% FWUE relative to S1 and D1 but increase yield significantly and increase FWUE 39.18% compare to F3 treatment with significant yield increasement.

Table 7.1 **Irrigation efficiency and irrigation management system evaluation parameters**

Treatment	Grain Yield (t/ha)	GY rainfed (t/ha)	ET_c (mm) Before Irrigation	ET_c (mm) After Irrigation	Number of Irrigation	Irrigation Amount (mm)	WUE (kg/m^3)	IWUE (kg/m^3)	FWUE (kg/m^3)
S1	8.44	2.90	157.5	262.8	3	90	2.01^{b}	9.38^{a}	3.7^{a}
S2	9.21	2.90	157.5	291.4	5	150	2.05^{ab}	6.14^{c}	3.2^{b}
S3	9.13	2.90	157.5	307.3	7	210	1.96^{bc}	4.35^{e}	2.62^{d}
D1	8.28	2.90	157.5	274.9	3	90	1.92^{cd}	9.2^{a}	3.63^{a}
D2	9.53	2.90	157.5	300.0	5	150	2.08^{a}	6.35^{c}	3.31^{b}
D3	9.37	2.90	157.5	310.1	6	180	2^{b}	5.2^{d}	2.95^{c}
F1	8.26	2.90	157.5	286.2	2	120	1.86^{d}	6.88^{b}	3.2^{b}
F2	9.07	2.90	157.5	298.3	3	180	1.99^{b}	5.04^{d}	2.85^{c}
F3	8.99	2.90	157.5	319.3	4	240	1.88^{cd}	3.75^{f}	2.38^{e}
LSD (0.05)							0.074	0.229	0.115
Irrigation Method							**	**	**
Irrigation Scheduling							**	**	**

*	Significant Level at 5% (α =0.05)
**	Significant Level at 1% (α =0.01)
ns	Non-Significant at 5% (α =0.05)

7.4 Evaluation of Irrigation Systems Efficiency

The irrigation efficiencies decreases with increasing irrigation amounts because the grain yield did not increase linearly (Li et al., 1995) and shows linearly increasing ET (Table 7.1). Irrigating winter wheat with SDI at soil water content of 50%, 60% and 70% of FC increases WUE by 2.9%, 4.7% and 6.3% whereas IWUE increased by 33.7%, 26.1% and 39.0% compare to FI under same irrigation scheduling. Similarly, irrigating with SI will increase WUE by 7.9%, 3.1% and 4.2% as well as increases IWUE by 36.3%, 21.8% and 16.0% in comparison to FI with corresponding irrigation scheduling of 50%, 60% and 70% respectively. As the irrigation water applied is the most concern part of the study has been estimated that 180.27 mm irrigation water (about 318.17 mm of total water including rainfall) is the optimal requirement to produce highest grain yield. This can be achieved by 6 irrigations by SDI and SI or 3 irrigations by FI systems, irrigating with 30 mm and 60 mm of irrigation water respectively for each. In this way while irrigating with SDI at SWC of 50%, 60% and 70% of FC will lead to save 25%, 16.67% and 25% of irrigation water respectively, relative to FI under same irrigation scheduling. Kharrou et al. (2011), found 20% irrigation water saving in drip irrigation compare to surface irrigation for winter wheat has found true in this study. Similarly, SI has found 25%, 16.7% and 12.5% respectively with same level of FI treatments. The treatment S1 has found more efficient than D1 because of slightly higher grain yield in S1.

7.5 Evaluation of Irrigation System on the Basis of Yield Parameters

7.5.1 Grain yield and evapotranspiration with total irrigation amount

The effect of irrigation amount on grain yield and ET was found quadratic and linear relationship respectively as shown in fig 7.1. Using the quadratic equation for grain yield Vs applied irrigation amount (mm), it can be calculated the optimal amount of irrigation for winter wheat to achieve maximum grain yield should be about 180.27 mm. Thus it shows that further application of irrigation water beyond 180.27 mm (318.17 mm total water) or producing more water stress will drastically reduce the grain yield.Liu et al. (2011b), had calculated 185 mm and 186 mm irrigation water respectively in first and second seasons of his experiment to optimal grain yield by sprinkler irrigation system. This proves that irrigating winter wheat maximum 6 times, 30 mm each with SDI or SI system or 3 times, 60 mm each with FI will leads to obtain maximum grain yield. The ET has linearly increases with the increasing amount of applied irrigation water and shows the similar correlation coefficient as found by Sun et al. (2006) and Wang et al. (2015). This concluded that more irrigated field increase ET but not increase grain after optimal irrigation amount.

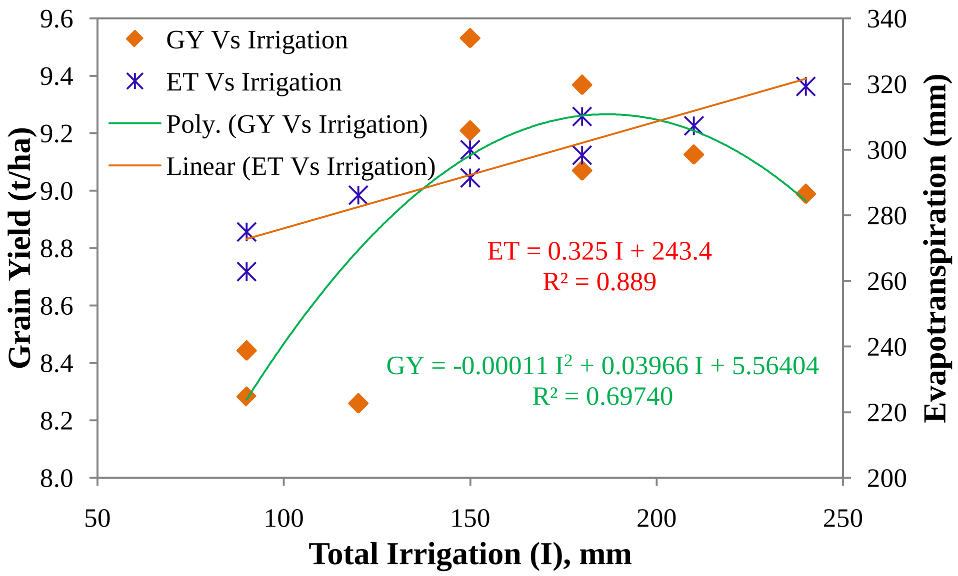


Figure 7.1 **Inter-relationships of grain yield (GY) and evapotranspiration (ET) with total irrigation water (I)**

7.5.2 Grain yield and straw yield with evapotranspiration

Grain yield and straw yield of winter wheat, both had found linear relationship with ET (Fig. 7.2) and found consistent linear relations given by Zhang and Oweis (1999) for grain yield and ET. Hao et al. (2014), also found linearly increasing wheat yield with increasing ET for NCP. The grain yield was linearly related to seasonal ET with a slope of 1.8 kg m^{-3}, which is approximately similar values (1.73 kg m^{-3}) given by Zhang et al. (1999) in piedmont region of NCP.

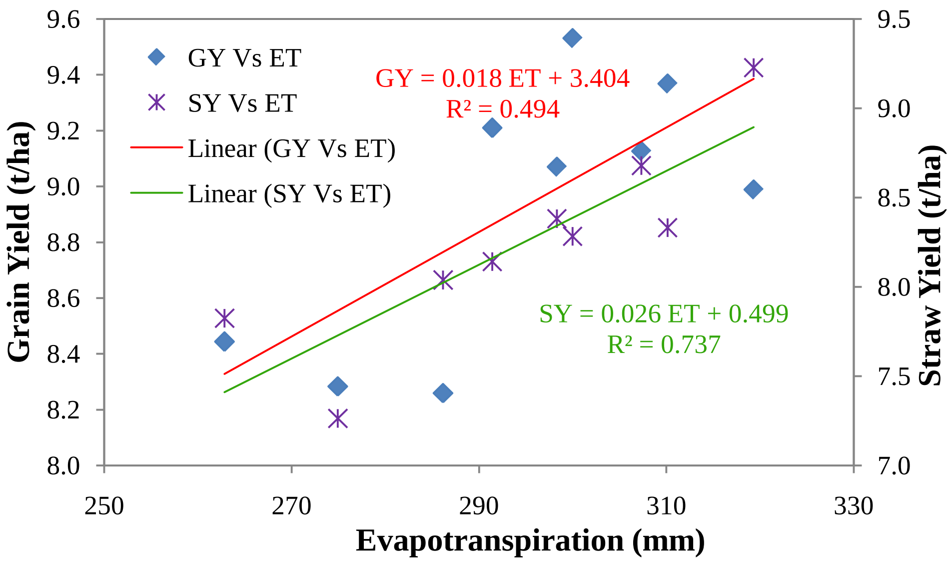


Figure 7.2 **Grain yield and straw yield relationship with evapotranspiration**

As in the previous section we have found that the GY has quadratic function with irrigation amount whereas ET increases linearly but here we have found GY linear (not quadratic) function with ET. This is because ET was controlled by meteorological factors as well as plant factors whereas irrigation depends on meteorological factors, plant factors, and soil conditions also soil water storage (Sun et al., 2006).

7.5.3 Grain yield and straw yield with root water uptake

The study has mainly focused on the root water uptake (RWU) which plays very important role in determining the grain yield. The grain yield Vs root water uptake shows poor (R^2 = 0.34) positive linear correlation (Fig 7.3). This maybe because of 70% IST, where RWU increases but grain yield decrease to some extent compare to 60% IST under same irrigation method but it shows increasing grain yield trend than 50% IST. On the other hand, the straw yield was found very well (R^2 = 0.738) linearly increasing correlation with increasing RWU. The treatments F3, S3 and D3 which continuously produce more RWU receive more water than treatments with 60% IST this lead to increase straw yield significantly and hence shows better correlation with increasing RWU. This shows that increasing RWU with increasing applied irrigation amount do not increase grain yield always but can influenced the vegetative growth. This also reviled that grain yield can't increase only by increasing RWU if optimum RWU will not obtained by proper irrigation scheduling.

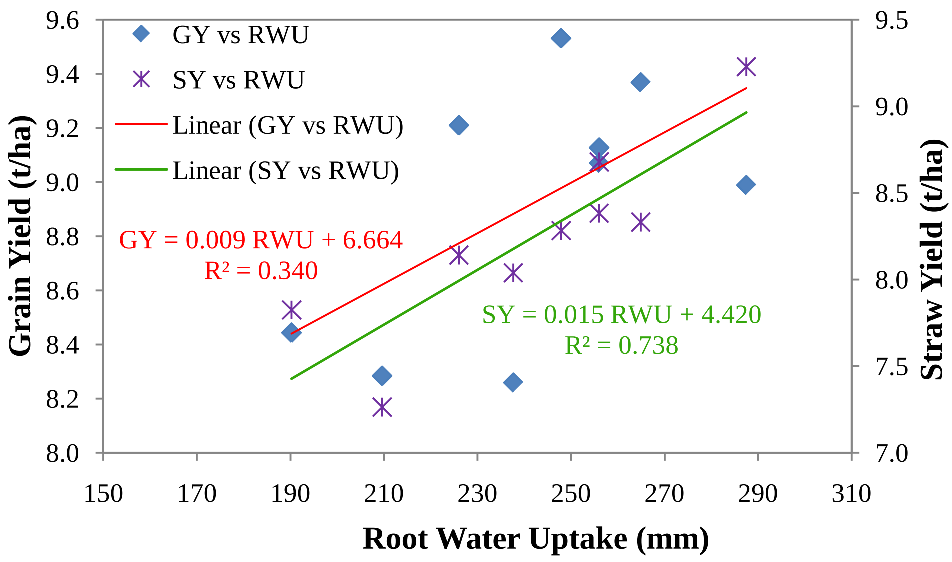


Figure 7.3 Grain yield (GY) and Straw yield (SY) Vs Root water uptake (mm)

7.5.4 WUE and IWUE with total irrigation amount

Water use efficiency (WUE) and irrigation water use efficiency (IWUE) shows respectively quadratic ($WUE = -0.000018 \times I^2 + 0.5563 \times I + 1.581206;\ R^2 = 0.348$) and linear ($IWUE = -0.037 \times I + 12.10;\ R^2 = 0.941$) function with total irrigation water applied (Fig 7.4). The impressive correlation has found between IWUE and total irrigation amount with higher correlation coefficient (R^2 = 0.941), this reviled that the IWUE decreases with more irrigation amount.

The WUE has been estimated to gain maximum with the irrigation amount of 154.53 mm. This shows that irrigating winter wheat 5 times, 30 mm each with SDI or SI and not more than 3 times, 60 mm each with FI will give satisfactory WUE, which can be achieve with irrigation scheduling at 60% of FC in either irrigation method.Sun et al. (2010), obtained similar relationships of WUE and irrigation amount with R^2 = 0.4298, 0.2747 and 0.437 for winter wheat in dry, normal and wet years respectively and calculated 186, 161 and 99 mm of irrigation water for maximal WUE in corresponding seasons.Li et al. (2005), had found that the soil water use (SWU) in the 2 m soil profile and irrigation water use efficiency (IWUE) was negatively related to the irrigation water volume. He concluded that applying 75 mm irrigation reduced SWU by 28.2 mm.

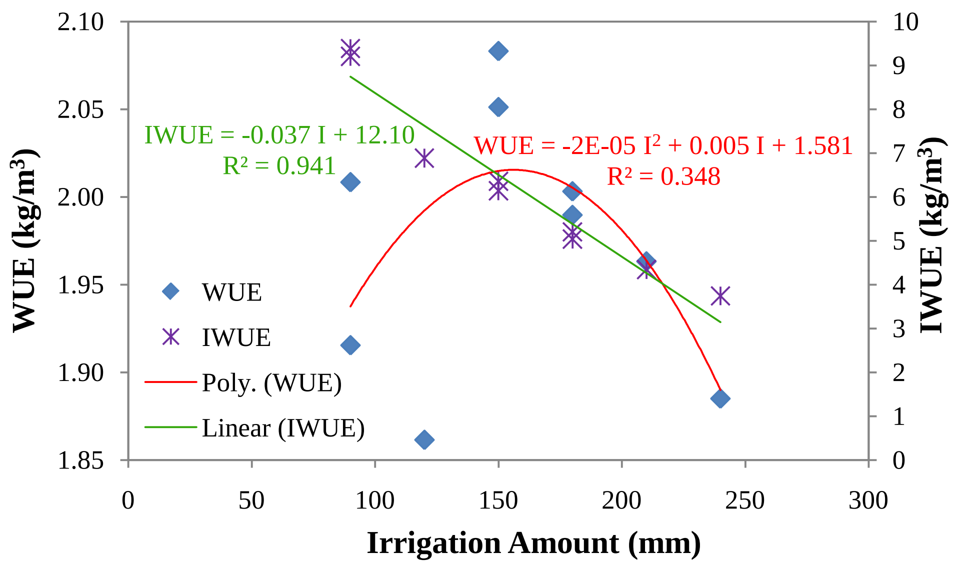


Figure 7.4 **WUE and IWUE relationship with total applied irrigation water**

7.5.5 Grain yield and water use efficiency

Grain yield (GY) and water use efficiency (WUE) both give quadratic function with total applied irrigation water and had found that either at soil water stress condition or surplus soil water, the GY and WUE both correlate negatively (Fig 7.1 and 7.4), whereas the optimal GY and WUE was achieve at favorable SWC (60% of FC). Similar prediction has been made by, Liu et al. (2011b) for sprinkler irrigation who have obtained highest yield with irrigation depth of 0.625-0.75E (E is the surface evaporation) and found reduced GY as well as WUE either lowering or adding irrigation water. As explained above, the maximum grain yield can be achieved at 180.27 mm (Fig 7.1) and the highest WUE can be achievable at 154.53 mm of irrigation water. Hence it concluded that the optimal irrigation scheduling and water application method should be chosen to assure irrigation water between 154.53 mm to 180.27 mm to keep both yields and WUE at relatively high levels. Based on the sensitivity indices to water stress at various growth stages, optimized irrigation schedule for high yield, efficient use of water and a net profit from winter wheat were established using one, two and three irrigations (60 mm of water per irrigation) in wet, normal and dry years respectively (Zhang et al., 2003; Zhang and Wang, 2002)

7.5.6 Grain yield and irrigation water use efficiency

This study has found very good linearly decreasing correlation between IWUE and applied irrigation amount but the GY has found parabolic function (Fig 7.1 and 7.4). This indicate that IWUE was optimum at lowest irrigation amount and decreases linearly with increasing irrigation but grain yield reaches to maximum level while increasing irrigation amount up to the level of 180.27 mm after that it also decreases. The predicted IWUE (Fig 7.4) for optimal irrigation amount of180.27 mm was found to be 5.43 kg/m^3 which can be achievable from S1, D1, F1, D2 and S2 but the grain yield in S1, D1 and F1 has drastically reduced whereas GY in D2 and S2 has found same level (not significantly different). This concluded that to assure maximum yield and obtain optimal IWUE, winter wheat should be irrigated either by SDI or SI as soon as soil water content reaches to 60% of FC.

7.5.7 Correlation between water use efficiency and harvest index

It has found good correlation (R^2 = 0.522) between harvest index (HI) and water use efficiency (WUE) as shown in fig 7.5. Similar relationship has been found by Zhang et al. (2010) for WUE and HI for different irrigation scheduling with correlation coefficient (R^2) of 0.395.Thus it can be reviled that WUE was accompanied by increase in grain yield and harvest index.

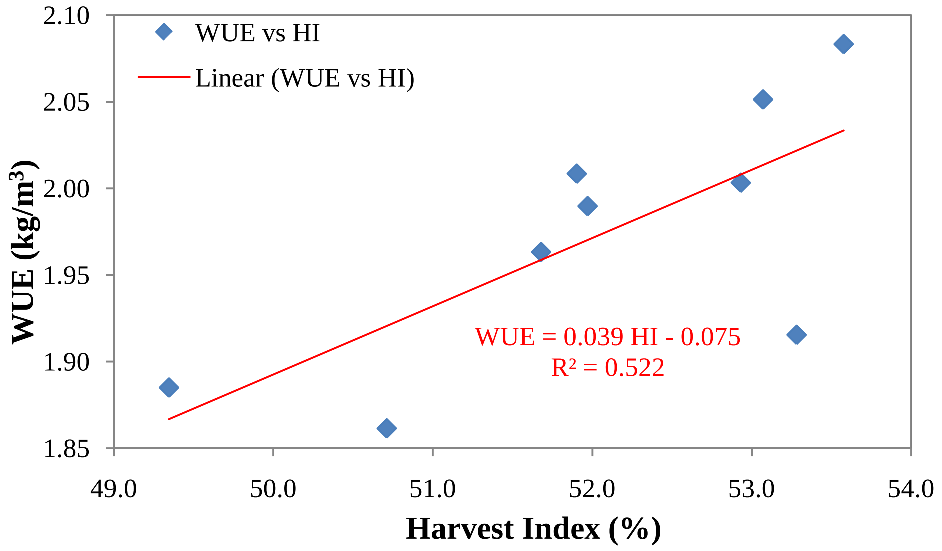


Figure 7.5 **Relationship between Water Use Efficiency and Harvest Index (HI)**

7.6 Conclusion

Irrigation practice is the key factor influencing the productivity. Very impressive correlation was derived for comparative management of thee irrigation water application method with three irrigation scheduling. It has found that decreasing irrigation amount will increase WUE up to some limits after that further deduction in irrigation amount will decrease WUE but IWUE still found increasing at lowest irrigation amount. The decrease in WUE at lowest water application is because of decrease in grain yield production. The SDI has proven the best option to increase either WUE or IWUE and can go for SI system to receive satisfactory efficiencies whereas FI has never found competent to prove better WUE or IWUE at any irrigation scheduling. The correlation function between WUE and grain yield conformed that the optimal irrigation scheduling and water application method should be chosen to assure irrigation water between 154.53 mm to 180.27 mm to keep both WUE and grain yields at relatively high levels. From the experimental results it has concluded that to assure maximum yield and obtain optimal IWUE, winter wheat should be irrigated either by SDI or SI as soon as soil water content reaches to 60% of FC.

General Conclusion and Recommendation

General Conclusion of the entire study

Optimum irrigation water management is essential to sustain high winter wheat yield and to increase its water use efficiency (WUE) in relation to the serious constraints of water resource situation in the North China Plain (NCP). A field experiment conducted for two cropping seasons (2013-14 and 2014-15) to study the effect of different irrigation methods with scheduling on crop growth below and above the soil surface had provided very compressive results in irrigation water management practice for winter wheat in the NCP.

It has been concluded that soil water content, root growth and soil temperature which vary with water application methods and irrigation scheduling, plays an important role in determining the root water uptake (RWU) and finally affects the overall soil water dynamics of cultivated winter wheat field. About 86-94% roots at 70% irrigation exist in SDI followed by SI, more than 81-83% roots at 60% in SI followed by SDI and more than 73-77% at 50% in SDI followed by SI were found in upper 60 cm soil profile found main factor in absorbing about 90% of the total water uptake for this reason where most of the root exists. The RWU converges in deeper soil profile accordingly with high frequency irrigation scheduling by different water application methods. This can be concluded as application of irrigation water more than that can hold by upper 60 cm soil profile will not utilize properly by crop. The deficit irrigation 50% of FC enhanced deeper root growth and found utilizing soil water from deep soil profile. Soil temperature which changes with irrigation method and scheduling becomes the key factor in controlling root branching and its profile growth rate. Due to higher surface soil temperature and lesser soil temperature with depth create temperature gradient and hence influenced the RWU. The higher soil moisture keeps shifting the root growth in upper 60 cm soil profile leaded by SDI.

Irrigating winter wheat at 70% lead to increased plant height in SI followed by FI and LAI in FI followed by DI. The effective tillers, panicle length, harvest index, number of kernel per panicle, and test weight which known as the productive parameters for winter wheat consistently found higher in SDI irrigating at 60% of FC. These factors found main reason in determining the highest grain yield and water use efficiency (WUE) for SDI treatment for 60% irrigation. The relationship between grain yield and applied irrigation amount is a parabolic function. The grain yield increases up to irrigating 180.27 mm, reaching the peak (9.53 t/ha) and then dropped for further irrigation amount providing seasonal rainfall about 137.9 mm. This proves that higher amount of irrigation does not necessarily result in higher yield. Similarly, the WUE has been estimated to gain maximum value with the irrigation amount of 154.53 mm (292.43 mm including rainfall).These shows, irrigating about 150 mm to 180 mm will make winter wheat cultivation sustainable at the NCP. Irrigating winter wheat with surface drip irrigation not only increase grain yield and WUE but also proved economical than SI and less extensive work than FI. Sprinkler irrigation perform better than surface flooding in producing higher yield and WUE but its initial investment is too expensive than SDI and FI also need higher pressure and should need to care for wind during the irrigation.

Irrigation water management requires timely application of the right amount of water, which is possible to control by appropriate irrigation water application method. This study concluded to schedule irrigation water application as soon as soil moisture reached to 60% of the field capacity will perform best in this region in the NCP. Irrigating wither wheat with 60% of FC can tolerate dry and wet season without any reduction of grain yield. Limited irrigation restricts crop yield in the North China Plain, where high level of production depends largely on irrigation. Establishing the optimal irrigation scheduling according to the crop water requirement (CWR) and precipitation is the key factors to achieve rational water use.

To choose an irrigation method, the farmer must know the advantages and disadvantages of the various methods. He or she must know which method suits the local conditions best. Unfortunately, in many cases there is no singles best solution: all methods have their advantages and disadvantages. Testing of the various methods- under the prevailing local conditions- provides the best basis for a sound choice of irrigation methods. This dissertation report provides very broad guidance and indicates several important criteria in the selection of a suitable irrigation method with feasible irrigation scheduling.

Recommendations

The relationships encountered between crop, climate, water and soil are very complex. Many biological, physiological, physical and chemical processes are involved. This field research study has deal with the method and timing of irrigation water application in winter wheat at North China Plain. Application of this research outcome are recommended for planning, design and operation of irrigation schemes and will be helpful to analyze the effect of irrigation as well as total available water supply on crop yield. All the other factor may have influenced the presented data will be the part of separate study for future research. The research output recommendations are outlined as follows:

i. Farmers of NCP need to adopt surface drip irrigation (SDI) as their first choice and can go for sprinkler irrigation (SI) considering the economical benefit in long term and sustainable agriculture farming.

ii. Depending upon the weather condition and seasonal rainfall distribution five to six irrigation were recommended for surface drip irrigation and sprinkler irrigation with 30 mm of irrigation water per irrigation and restrictedly regret using flood irrigation (maximum of three irrigations with 60 mm each irrigation) until unless fail to manage drip or sprinkler irrigation.

iii. Irrigating at 60% of field capacity in either irrigation method can provide favorable soil water environment in root zone optimizing the root water uptake to produce maximum grain yield and achieve highest water use efficiency.

iv. The nutrient use efficiency and the microbial activities beneath the soil surface and the micro climate above the soil surface greatly affect by irrigation method and irrigation scheduling which were the missing parts of this study.

v. Flood irrigation (FI) enhance contaminating surface nutrient and other soluble ions to the ground water, need to compare with SDI and SI as an additional convincing factor for NCP farmers and can reduce further ground water pollution. Similarly, the groundwater table depletion and recharge in FI, SI and SDI method with irrigation scheduling will be the interesting and fruitful research for NCP plains.

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Acknowledgement

This formal acknowledgement may not really express depth of feelings and emotion I have, towards the persons and institutions, which contributed to my study and dissertation work. The author would like to take the opportunity to humbly express his endless regard, profound gratitude and sincere homage to the omniscient and almighty God Shree Krishna, The Lord of the Universe, for his never ending mercifulness blessing in the successful completion of this research work, preparing the dissertation and keeping in sound health during the stay in China.

The author wishes to express his heartfelt sense of gratitude, sincere appreciation, profound respect and immense indebtedness to his benevolent supervisor Professor Duan Aiwang, Director General's, Farmland Irrigation Research Institute (FIRI), Chinese Academy of Agricultural Sciences (CAAS), Xinxiang, Henan-453003 for his scholastic guidance, vigilant supervision, valuable instruction, constructive criticism and constant encouragement during every phase of research work and bringing the experimental results in the present informative shape. His guidance during this study period will be memorable forever and will be the historical wonderful moment of the author's life.

The author feels proud and great pleasure to express his deep gratitude and sincere appreciation to his most respected teachers Dr. Gao Yang, Associate Professor and Dr. Liu Hao, Associate Professor, Key Laboratory of Crop Water Use and Regulation, Ministry of Agricultural, FIRI: CAAS, Xinxiang, Henan-453003 for his continuous guidance, knee supervision, kind supports during the research work and presenting his love as elder brother.

The author would like to take opportunity to extend his grateful and sincere thanks to Professor Sun Jingsheng, the Dean of Key Laboratory of Crop Water Use and Regulation and simultaneously express his special thanks to Dr. Zhaorong Mi, Dr. Shen Xiaojun, Dr. Liu Zhandong, Dr. Huang ling, Zhang Yingying, and all other teachers as well as the staffs of the laboratory or from institute for their continuous supports and encouragement.

The author believe that his stay in China becomes comfortable and pleasant because of his best friend Dr.Wang Guangshuai, Dr. Liang Yueping, Dr. Sun Chitao, Zhou Haoyong, Si Zhuanyuan, Dr. Zhang Hao, Dr. Nurolla Magzum, Wu Xiaolei, Chen Xinguo, Dr. Gong Xuewen, Steve, Dr. Priya Lal Biswas, Dr. George Oluoch, Dr. Samesh Adhakari, Dr. Neena Gorkhali and Dr. Sanjay Jha whose supports and endless love makes its memorable. The author also extend his thanks to workers who helped for extensive field work and all other friends as well as institution for kind supports, valuable comments, suggestions and faithful blessing during the study period.

The author is grateful to Chinese Scholarship Council (CSC) and Graduate School of Chinese Academy of Agricultural Science (GSCAAS) for providing great opportunity with respectable scholarship to pursue PhD at Farmland Irrigation Research Institute (FIRI). And extend his thanks for the financial support from the China Agricultural Research System (CARS-3-1-30), the Special Fund for Agro-Scientific Research in the Public Interest (201203077), the Chinese National Natural Science Fund (51309227), and The Agricultural Science and Technology Innovation Program (ASTIP), Chinese Academy of Agricultural Sciences to carry out experimental study.

Last but not the least the author extends his heartiest gratitude and endless love to his all family members specially his dearest parent and younger brother for their company, keep blessing, inspiration encouragement and moral support during his stay in China. Author believes his father and mother in low equally contributed their efforts for peaceful stay in China. The author finally would like to dedicate this dissertation to his beloved wife as well as lovely daughter Sneha Jha and Shruti Jha who always being his heart beat, sacrificed a lot and keep endless patient, praying every moments which bring this happiness and paved the way in achieving PhD degree at Graduate School of Chinese Academy of Agricultural Science (GSCASS).

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