Temporal Variability of Soil Hydraulic Properties under Different Soil Management Practices

by

Shahid Maqsood Gill

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ABSTRACT

TEMPORAL VARIABILITY OF SOIL HYDRAULIC PROPERTIES UNDER DIFFERENT SOIL MANAGEMENT PRACTICES

Shahid Maqsood Gill
University of Guelph, 2012

Advisor:
Dr. Gary W. Parkin

Agricultural management practices including tillage and irrigation have a considerable effect on soil physical and hydraulic properties in space and time. Tillage practices initially alter the soil physical and hydraulic properties depending on the type and depth of tillage. These changes are reverted back to original conditions due to reconsolidation during cycles of wetting and drying. Irrigation techniques can manipulate the reversion process dynamically due to different modes of wetting. The combined effects of tillage and irrigation have rarely been investigated. Therefore, two experiments were conducted to investigate the effect of different tillage practices and irrigation techniques on soil physical properties and temporal variations in soil hydraulic properties, one on wheat and second on the following maize crop grown on the same plots. The tillage and irrigation treatments implemented for the wheat crop were repeated for the subsequent maize crop restoring the same treatment layout plan. Intact soil core samples were collected, in the middle of the wheat crop before irrigation and the end of the maize crop season, for the determination of soil physical and hydraulic properties. Field saturated hydraulic conductivity ($K_{fs}$) was determined using
the Guelph pressure infiltrometer method and volumetric soil water content ($\theta_v$) and potential ($\psi_m$) was measured in the field using water content sensors and tensiometers, respectively. The wheat crop received rain showers from time to time, while in maize, a heavy spell of monsoon rains following tillage caused most of the soil reconsolidation. So, the greater intensity of rains, rather than the cycles of wetting and drying, became primarily responsible for the differences in soil physical and hydraulic properties between the two crops. Moldboard plow resulted in an increase in yield and improvement of soil hydraulic properties during both crop seasons. Flood irrigation reverted back the effects of tillage on soil hydraulic properties greater than sprinkler irrigation, while it did not affect the yield significantly. The dynamics of volumetric soil water content ($\theta_v$) differed, depending on tillage type, irrigation technique and crop season. Moldboard plow was the wettest after rain or irrigation events but it dried quicker than other tillage treatments. Flood irrigation caused higher wetting than sprinkler irrigation. These wetting effects were greater in wheat as compared to maize crop. Temporal variability calculated as time averaged relative difference in $\theta_v$ was greater during wheat as compared to maize, while temporal stability calculated as standard deviation of temporal stability decreased with flood irrigation in both crops. Soil bulk density ($\rho_b$) and water retention characteristics ($\theta_v(\psi_m)$) measured on the intact soil cores and total porosity ($\varphi$), plant available water capacity ($\theta_{PAWC}$) and pore size distribution calculated from water retention data depended on the time of sampling. During wheat, the $\rho_b$ was lower resulting in a higher $\varphi$ than after maize. Moldboard plow decreased $\rho_b$, increasing $\varphi$, while the effect of flood irrigation was
opposite in both crops with greater magnitude in wheat. Similarly, the effects of tillage on $\theta_v(\psi_m)$ were observed in both crops, while those of irrigation were observed in maize only. Cultivator treatment retained higher $\theta_v$ at higher $\psi_m$ (−30 and −100 kPa), followed by chisel and moldboard plow. Plant available water capacity ($\theta_{PAWC}$) was greater in maize as compared to the wheat crop. Cultivator had higher $\theta_{PAWC}$ than chisel and moldboard plow in both crops. Wheat had greater volume of larger pores (> 10 μm, $\varphi_{>10}$), whereas extraordinary rains as well as irrigations after tillage caused these larger pores to decrease in maize. Moldboard plow had higher $\varphi_{>10}$ at 10 cm depth in both crops with greater magnitude in wheat. Field saturated hydraulic conductivity ($K_{fs}$) determined before irrigations and at the end of both crop seasons was greater in wheat than in maize especially in the first determination. Moldboard plow exhibited greater $K_{fs}$ followed by chisel plow and cultivator in both crops and it decreased significantly with time in wheat but not in maize. Flood irrigation was responsible for a reduction in $K_{fs}$ and the effect was greater in wheat as compared to maize. It was concluded that a greater intensity of water application in the form of rains or irrigations can revert the changes in soil physical and hydraulic properties induced by tillage more effectively than the cycles of wetting and drying. Soil hydraulic properties may be optimized with the combination of suitable tillage and irrigation for efficient utilization of water resources.
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1.1 Introduction and Background

Temporal changes of soil physical and hydraulic properties have been the subject of much research to quantify the effects of different management systems within growing seasons, over cropping systems and between years. Agricultural management practices are applied as events with their transient effects realized over different time scales. The resulting variability in soil physical and hydraulic properties is dynamic in space and time. Both natural and human-induced variability have been characterized and quantified to various levels of detail. Many soil properties are strongly dependent on the dynamics of soil structure with the management systems being primary agents for changing the soil structural conditions (Alletto and Coquet, 2009). Soil physical properties which change with the variation in soil structure include bulk density, total porosity, pore geometry (size distribution, shape, continuity and tortuosity), penetration resistance and aggregate stability, consequently affecting soil hydraulic properties such as water retention characteristics, plant available water capacity, infiltration capacity and variably saturated hydraulic conductivity. These soil properties are dependent on seasonal climatic conditions, management practices, crop development and biological activity (Reynolds et al., 2007).
Temporal variability of soil physical and hydraulic properties can be even greater than spatial variability in agriculturally managed soils. The relative significance of different sources of variability (spatial and temporal at multiple scales, and management related factors) with soil type was evaluated by van Es et al. (1999) with the conclusion that the variability due to soil management and temporal processes was more significant than the field-scale spatial variability for medium and fine textured soils. Soil physical and hydraulic properties are expected to vary even during a crop cycle especially after tillage and irrigation or rain. Logsdon et al. (1993) concluded that within-season changes in infiltration rates could be greater than the management-induced differences and suggested that the rate measurements should be recorded soon after tillage and irrigation or rainfall events. More recently, Bamberg et al. (2011) documented that high levels of soil water content after irrigation events followed by drier soil conditions resulting from large rates of evapotranspiration caused modifications of soil physical and hydraulic properties throughout the crop production season.

Tillage and irrigation are the most influential soil manipulations having short-term effects on soil physical and hydraulic properties. Tillage leads to soil loosening depending upon the soil type, soil water content and the type of tillage operation. Surface soil conditions, resulting from different tillage practices are likely to contribute to spatial and temporal variability of the macropore system (Mohanty et al., 1994). Soil properties such as saturated hydraulic conductivity and pore size distribution for larger pore radii are often used as criteria to differentiate tillage system effects on soil
structure (Cameira et al., 2003). Logsdon et al. (1999) and Reynolds et al. (1995) reported that tillage disrupted the continuity of pores from the soil surface. In another study, Logsdon et al. (1993) found that no-tillage (NT) resulted in significantly higher ponded infiltration rates than did chisel or moldboard plow, while McCoy et al. (2006) observed greater drainage under conventional tillage (CT) than a no-tillage management system. On the other hand, Ankeny et al. (1990) found little effect of tillage on infiltration rates. Results of comparisons of NT and minimum tillage with various CT practices over different time periods have not been consistent across soils, climates, and experiments (Green et al., 2003; Strudley et al., 2008).

Soil physical and hydraulic properties due to tillage revert back to the original state as a result of natural reconsolidation due to wetting and drying cycles (Green et al., 2003) created by rain events or supplementary irrigation provided during the crop season. The reconsolidation is a dynamic process and it may depend on the frequency (Cameira et al., 2003), amount (Bandaranayake and Arshad, 2006) and method (Bandaranayake et al., 1998) of water application and subsequent drying. Consequently, the coupled effects of tillage and irrigation management can be a factor responsible for temporal variability in soil physical and hydraulic properties and processes. There are many studies in the literature highlighting the long-term effects of tillage on soil physical and hydraulic properties but less work is available on short-term (seasonal) effects. Secondly, very limited information is available on the dynamics of the temporal effects of irrigation on soil physical and hydraulic properties (Mubarak et al., 2009a; Mubarak et al., 2009b) especially when coupled with tillage management. Additionally, several
studies have focused on quantitative assessments and modeling of the spatial variability of soil hydraulic properties (Bormann et al., 1999; Herbst et al., 2006; Iqbal et al., 2005). However, the temporal dynamics of soil hydraulic characteristics is commonly not taken into account in models, primarily because its measurement is costly and time-consuming (Angulo-Jaramillo et al., 1997). This review of the literature focuses on the studies on effects of tillage and irrigation on temporal variability of soil physical properties and the needs and challenges for future work as background information for this thesis.

1.2 Tillage and Irrigation Management Effects on Soil Properties

Tillage is the most widely researched management practice affecting soil physical and hydraulic properties and processes. The terminology for tillage practices varies geographically and culturally. The CT practices are not similar in different parts of the world. Multi-tine cultivator, moldboard plow, chisel plow etc. are used as CT practices at different places with moldboard plow mostly used as CT. However, CT practices whatsoever will be lumped together in this review. In some cases, minimum tillage (MT) or reduced tillage (RT), which is the tillage practice in between CT and NT, have been compared with CT and NT. These tillage practices manipulate the soil and potentially alter its structure differently resulting in variability in temporal dynamics of the soil physical and hydraulic properties which are unstable (Strudley et al., 2008). These effects of tillage on soil physical and hydraulic properties will now be discussed in detail.
1.2.1 *Soil bulk density and total porosity*

Soil bulk density and total porosity along with penetration resistance are the most commonly measured soil physical properties affected by tillage. They are primarily used as measures of soil compaction which may adversely affects soil hydraulic properties and processes. The bulk density and penetration resistance have been found to increase with the number of traffic passes while air permeability decreases with increased traffic intensity (Ohu et al., 2006). Voorhees (1983) studied the ability of tillage to ameliorate wheel track compaction and concluded that the moldboard plow was better able to decrease bulk density and to lower penetrometer resistance than was either the chisel plow or natural processes. Deep tillage (45 cm) returned the soil physical properties of the compacted plots to their original un-compacted, not deep tilled conditions (Abu-Hamdeh, 2003).

Tillage, irrigation and cropping systems can influence bulk density, but any change in bulk density as a result of changing management practices is likely to be detected nearer the soil surface (Dam et al., 2005; Wuest et al., 2006). Numerous studies have investigated the effect of tillage practices on bulk density. Ismail et al. (1994) found no differences in bulk density between NT and CT, while Lal et al. (1994) found bulk density was 7% lower for NT versus CT in continuous corn, corn-soybean, and corn-oat-meadow rotations. Lal et al. (1994) concluded that after 28 years of consistent tillage, bulk density was lowest in NT due to the retention of more crop residue on the soil surface than in conventional tillage. However, opposing trends can be found in the literature. Dam et al. (2005) and Kushwaha et al. (2001) found that near-
surface bulk density was 10% higher in NT than in CT. A study comparing moldboard plow systems and NT systems by Mielke et al. (1986) on seven soils at two depths showed a greater bulk density for the NT system in six soil × depth combinations, while a greater bulk density for the moldboard plow system in one and no bulk density differences between systems in seven soil × depth combinations showing a tendency for greater bulk densities in NT systems. Others have also found that NT results in a higher bulk density near the soil surface than intensive tillage (Douglas et al., 1986; Kay and VandenBygaart, 2002; Schjønning and Rasmussen, 2000; VandenBygaart et al., 1999).

Most studies on fine-textured soils show that soil bulk density is higher under NT than under CT systems (Gantzer and Blake, 1978; Kladivko et al., 1986), but some studies have found no differences related to soil texture (Blevins et al., 1983).

Tillage methods contribute differently to soil bulk density and porosity changes. Schwen et al. (2011) compared moldboard plowing and chisel plowing with NT on a silt loam soil cropped with winter wheat for two years. They observed higher bulk density and lower total porosity under NT compared to CT and RT. Erbach et al. (1992) evaluated the effect of NT, chisel plow, moldboard plow, and para plow systems on poorly drained, medium, and fine textured soils in Iowa and found that all tillage tools reduced bulk density and penetration resistance to the depth of tillage. However, after planting, only the soil tilled with the para plow remained less dense than before tillage over the year. Voorhees and Lindstrom (1984) showed that porosity, bulk density, and mean diameter of soil aggregates changed from the time of initiation of a tillage experiment both within a tillage system and for comparison between tillage systems.
They inferred from their results that soil properties were more representative of the tillage system after 4-7 years of continuous tillage than at the initiation of the tillage system. They also emphasized the need to use long-term tillage studies for measurement of tillage effects on soil physical properties.

Irrigation also contributes to the changes in soil bulk density. Lehrsch and Kincaid (2010) observed that a single sprinkler irrigation of 127 mm at 70 mm h$^{-1}$ increased the bulk density of near-surface 34 mm of a structurally unstable silt loam from 1.02 to 1.20 Mg m$^{-3}$. Cameira et al. (2003) reported that, in a cultivated maize experiment, seven surface irrigation events resulted in a continuous reduction in macroporosity until close to harvest when it increased, probably due to root development.

Most publications document long-term averaged comparisons between hydraulic properties after different tillage practices and do not take into account the spatial and temporal dynamics (Strudley et al., 2008). Only a few published studies address both the long-term temporal and management-induced changes in soil bulk density and porosity (Alletto and Coquet, 2009; Angulo-Jaramillo et al., 1997; Bormann and Klaassen, 2008; Cameira et al., 2003; Daraghmeh et al., 2008; Messing and Jarvis, 1993; Moret and Arrúe, 2007). Long-term temporal variability has been found to exceed the management-induced changes in soil bulk density (Alletto and Coquet, 2009), while an opposite trend has been observed by others (Hu et al., 2009; Schwen et al., 2011). Although the importance of this variability was demonstrated, it still has not been well studied.
1.2.2 Soil structure and aggregate stability

Maintenance of stable soil structure is an important issue from both agricultural and environmental aspects. Tillage directly affects soil structure by mechanically breaking and macro-aggregates into smaller units and indirectly through its effect on root growth, biological processes and soil organic matter content. Soil properties such as soil structure, aggregate stability and porosity are often used as the criteria to differentiate tillage system effects on soil physical and hydraulic properties (Mielke et al., 1986; Voorhees, 1983; Voorhees and Lindstrom, 1984). An account of the classification of the soil pore system and its dependence on the stability and size distribution of soil aggregates and soil structure has been explained by Kutílek (2004).

Kushwaha et al. (2001), while studying changes in the proportions of water stable aggregates (WSA) due to reduction in tillage from conventional to minimum and zero tillage, found 27 to 45% increase in mean weight diameter (MWD) of soil aggregates and crop residue retention had added benefits increasing MWD by 71 to 98% with tillage reduction. Abid and Lal (2008) observed higher total WSA, geometric mean diameter (GMD) and MWD of soil aggregates in NT than chisel plow. They also observed that the macro-aggregates (> 0.25 mm) were more abundant in NT, while micro-aggregates were more abundant in chisel plowed plots. Álvaro-Fuentes et al. (2008) concluded that soil aggregation increases with the decrease in the intensity of tillage.

Cropping systems also influence soil aggregation in addition to tillage. Friedel et al. (1996), Hussain et al. (1999) and Liebig et al. (2004) concluded from their studies, with different crop rotations including cereals, legumes and oilseeds, that aggregate
stability of the upper soil layer was greater in MT and NT compared to CT. The cereals-based cropping systems had greater soil aggregate stability as compared to the others. Root development and soil microorganism activity during the vegetative crop growth result in the formation and stabilization of soil aggregates and long fallowing may lead to a decrease in soil aggregation and structural stability (Álvaro-Fuentes et al., 2008). Kong et al. (2005) observed that incorporation of legumes in the cropping system and addition of composted manures enhance soil aggregation.

Dexter (2004a, b, c) defined a soil physical parameter \( S \) as an index of soil physical quality. It is a measure of soil microstructure that controls many key soil physical properties and can be quantified from water retention data. Values of \( S \) can be used to obtain quantitative estimates of the optimum water content for tillage, the degree of soil break-up during tillage, the size distribution of clods and aggregates produced by tillage and soil structural stability (Dexter and Birkas, 2004; Dexter and Czyż, 2007; Dexter and Richard, 2009; Keller et al., 2007). Soils having larger values of \( S \) produce smaller aggregates after tillage and they may be tilled over a wider range of water contents with satisfactory results (Dexter et al., 2005). Factors that cause soil degradation, such as compaction and reduction of organic matter content, reduce the value of \( S \) and hence have the consequence of coarser soil structures being produced by tillage (Dexter and Richard, 2009). It was shown that the optimum water content for tillage occurs when the matrix porosity is mostly saturated, but the structural porosity is mostly drained. They also explained soil crumbling due to tillage in terms of the ability of the air-filled micro-cracks comprising the structural porosity to expand and elongate.
while being resisted by the soil matrix stresses between the cracks. However, the mechanisms responsible for this have not been clearly defined.

Structure-related soil properties generally have a high natural spatio-temporal variability that interacts with the potential influence of agricultural land use practices. Temporal changes in soil aggregation during crop growth have been studied by several authors. Perfect et al. (1990) observed considerable fluctuation in the aggregate stability of a soil in Elora, Canada under a range of different crops and tillage practices over the growing season with an overall decline in stability during the summer months. The temporal fluctuation in soil structural stability within each of the cropping and tillage treatments was as large, or larger, than the changes observed between treatments. They concluded that the gravimetric soil water content at sampling was the soil factor that mostly influenced aggregate stability. Similar findings were reported by Angers (1992) and Chan et al. (1994).

1.2.3 Soil pore geometry

The processes considered dominant for the formation of soil porosity differ between tilled and untilled cropping systems. In the former, pores are formed by the rearrangement of the soil solids by the tillage tool, while in the latter pores are formed primarily by the biological activity with the action of earthworms and roots. In agricultural soils, management and tillage practices have a strong impact on the physical properties of the topsoil and the characteristics of the macropore system (Frede et al., 1994; Shipitalo et al., 2000; Tebrügge and Düring, 1999). The pore geometry, which is the
size distribution, shape, continuity and tortuosity of the soil pores, would be expected to vary between tilled and untilled cropping systems due to different methods of creation of pores. Soils under CT generally have lower bulk density and associated higher total porosity within the plough layer than under NT. The changes in total porosity are related to the changes in pore geometry depending on soil type. Schjønning and Rasmussen (2000) reported that direct drilling compared to moldboard plowing resulted in lower volume of macropores (>30 μm) on coarse sandy soil and silt loam, whereas the opposite effect was found on sandy loam at the time of plant emergence. Pore continuity indices calculated from air diffusivity and air permeability measurements showed that direct drilled soil had less continuous and more tortuous macropores than moldboard plowed soil. Roseberg and McCoy (1992) found that CT increased the total porosity but decreased the macropore continuity, while NT tended to preserve whatever pore geometry existed in the soil previously. Wahl et al. (2004) found higher macroporosity (> 1 mm diameter) for CT at 0-10 cm soil depth, while it was higher for conservation tillage at 20 cm and deeper soil depths. They also observed greater continuity of macropores the in vertical direction in soils under a conservation tillage system than CT as indicated by greater depth penetration of dye tracer. VandenBygaart et al. (1999) reported that the conversion from CT to NT resulted in a decrease in the number of pores of 30-100 μm diameter as the number of years in NT increased, while there was an increase in the number of pores of 100-500 μm diameter only after 4 years of NT. The greater numbers of macropores and higher connectivity of the macropore system in the vertical direction, which is found commonly in reduced tillage (RT)
compared with CT systems is mostly attributed to greater abundances of earthworms and less disturbance of the topsoil (Dunn and Phillips, 1991; Meek et al., 1990; Reynolds et al., 1995; Zachmann et al., 1987). In addition, irrigation has also been found to affect soil pore size distribution. Cameira et al. (2003) found that irrigation decreased the macro and mesoporosities of the ploughed layer by 65 and 50%, respectively. This was attributed to the breakdown of fragile pores created by tillage.

Water flow in structured soils is mainly conducted by macropores (> 75 μm) and larger mesopores (30-75 μm) even though they constitute only a small fraction of the total porosity (Moret and Arrúe, 2007; Mubarak et al., 2009b; Reynolds et al., 1995; Sauer et al., 1990). The dynamics of soil hydraulic properties have been estimated from these easier to measure variables, like hydraulically active structural porosities (Aimrun et al., 2004). The main impact of different tillage techniques on soil hydraulic properties is expected to occur in these structural pores due to changes in different groups of macro and mesopores. Daraghmeh et al. (2008) found that CT initially resulted in higher calculated effective porosities but later RT had the highest effective porosities. They also observed that traffic had a dominant influence on the effective porosities, which decreased down to 10% in CT and 20% in RT of the value shortly after tillage. Hydraulic conductivity and the infiltration capacity of soils are governed to a large extent by the volume fraction, diameter distribution, and continuity and connectivity of the macropore network (Logsdon et al., 1990; Shipitalo et al., 2000). The effect of soil tillage and management on transmission properties is not consistent. Results showed that untilled compared to tilled soil had greater (Arshad et al., 1999; McGarry et al., 2000),
similar (Ankeny et al., 1990) or lower infiltration rates (Gantzer and Blake, 1978; Gómez et al., 1999; Rasmussen, 1999). The inconsistencies can be associated with pore functioning. The flow-active pores are not frequently quantified during infiltration due to the required time-consuming measurements.

Temporal changes of hydraulic conductivity tend to be followed mainly by the changes of soil structure as affected by biological activities (Suwardji and Eberbach, 1998), soil settlement (Petersen et al., 2008), soil erosion processes (Genereux et al., 2008), and compaction (Alakukku, 1996a, b). Simultaneously, the relative contribution of pore size classes to water flow may change accordingly. Hu et al. (2009) observed that the contribution of macropores (> 0.5 mm) and mesopores (0.5-0.1 mm) generally decreased, while the contribution of micropores (< 0.1 mm) generally increased during a three-month period for different land uses. Mubarak et al. (2009b) studied the temporal effects of high frequency drip irrigation on soil hydraulic properties during a maize growing season. They observed that saturated hydraulic conductivity and mean effective pore radius decreased significantly after the first irrigation and kept on decreasing until the root system was well established. Once the root system was developed, both the parameters increased gradually due to biological activity. The knowledge of changing pore class contributions to water flow with time would better facilitate the understanding of underlying reasons for temporal changes in hydraulic properties.
1.2.4 Soil water retention characteristics

Soil water retention is an important soil physical property controlled by the soil pores. Soil pore size distribution facilitates the characterization of soil structure (Pagliai et al., 1998), which can be estimated by soil water retention curves (Arya and Paris, 1981). Changes in pore geometry resulting from tillage, as well as other disturbances, cause a change in water retention (Azooz et al., 1996). Tillage typically decreases the bulk density and increases total porosity, increasing the amount of water held at high soil water potentials and decreasing the amount held at lower potentials (Unger and Cassel, 1991). However, the response may depend on soil texture. Unger (1975) showed that disrupting the natural structure decreased the water retention of coarse-textured soils and increased the retention of fine-textured soils relative to that of natural soil cores at a matric potential of −0.033 MPa. At a matric potential of −1.5 MPa, disturbed samples of soil of all textures retained slightly more water than undisturbed samples, but the percentage change was greater for coarse- than for fine-textured soils. Besides the textural response, tillage may further influence water retention if it incorporates crop residues, or if it alters the distribution of sand, silt and clay in the soil by mixing these particles from different soil horizons (Unger and Cassel, 1991). If the pore geometry is deformed by external perturbations, such as compaction or shear, this will also affect water retention (Gregory et al., 2009; Richard et al., 2001; Wu et al., 1997).

The effects of tillage and management on soil water retention are often mixed. Comparing NT and CT systems, Arshad et al. (1999) and Azooz et al. (1996) found that soil water retention and storage capacity were higher under NT, while Seybold et al.
(2002) reported significantly improved infiltration rates, number of stable aggregates, and water content within the 0 to 7.6 cm soil depth range. Similarly, McGarry et al. (2000) found that zero tillage increased water storage, the final infiltration rate, and total infiltration. Twenty-eight years after establishing tillage treatments on a silt loam in Ohio, Mahboubi et al. (1993) found that NT resulted in a greater water retention as compared to CT. Chang and Lindwall (1989) did not observe any change in water retention of a clay loam 20 years after establishing tillage treatments in Alberta. Arshad et al. (1999) found that water retention of a silt loam was greater after about 12 years of NT versus CT in northern British Columbia. Allmaras et al. (1977) found no effect on soil water retention at greater than −8 kPa, but NT systems retained more water than chisel plow systems at lower potentials for a Walla Walla silt loam. Tollner et al. (1984) reported that moldboard plow resulted in greater soil water retention than NT at greater than −80 kPa but not at other potentials. Conversely, Lal (1999) found that tillage practices had no significant effect on soil water retention at all potentials on a Wooster silt loam. Lindstrom and Onstad (1984) observed that the increase in porosity by CT was mostly in the range of pores corresponding with greater than −60 cm pressure head. Results of Mapa et al. (1986) indicated that the changes in soil water retention (decrease in soil water contents) after tillage were mainly at soil water pressure heads greater than −300 cm. Hill et al. (1985) found in Mollisols from Iowa that chisel-ploughing retained more plant-available soil water than CT, attributable to the interaction of tillage with calcium and organic matter (OM). In Canadian soils, Diwu et al. (1998) found higher plant available water capacity (PAWC) under direct seeding than
under RT and CT. However, in a long-term experiment on a Hapludult (Hill, 1990), pore space available for storage of plant-available water was greater under CT than NT and utilization of total water resources appeared to be better than that under NT, simply because of higher soil water infiltration and lower soil water evaporation.

Bhattacharyya et al. (2006) observed that the soil under zero tillage retained more water than that under MT and CT, but water retention for soybean-wheat, soybean-lentil and soybean-field pea rotations was similar, indicating an absence of the effect of crop rotations on soil water retention. Bhattacharyya et al. (2008) found higher PAWC in direct seeding as compared to CT in rice and wheat crops following 4 years of rice-wheat rotation. They also investigated the effect of applying 1-4 irrigations at critical growth stages for both crops on PAWC and observed an increase with the number of irrigations attributing this effect to the increase in soil organic carbon.

The upper part of the soil will generally be unstable after tillage. Ahuja et al. (1998) reviewed the literature and reported that tillage temporarily increases water retention in the wet range. Zhai et al. (1990) examined the effect of tillage on temporal variability of soil water content ($\theta_v$). They observed large differences in $\theta_v$ between moldboard plowing and short- and long-term NT plots early in the season which persisted for several weeks, depending upon rainfall amount and distribution. In summary there remains limited published data in which the soil structures resulting from different tillage, stubble management, and irrigation regimes are quantified and related to water retention curves.
1.2.5 *Infiltration capacity and hydraulic conductivity*

For agricultural soils, tillage is a source of variability of soil hydraulic properties both in space and time (Coutadeur et al., 2002; Messing and Jarvis, 1993; Prieksat et al., 1994). The mechanical action of tillage implements modifies soil structure, porosity, crop residue distribution and surface roughness. Changes in soil hydraulic properties of the surface soil induced by tillage can alter the infiltration rate of rain or irrigation and significantly affect the subsurface drainage discharge. When a soil is tilled, the infiltration rate may increase due to an increase in total porosity, but it may decrease if continuity of the large pores is disrupted. The relative importance of these two factors depends on the degree of soil compaction (Kooistra et al., 1984). The proper use of tillage should, however, allow growers to maintain adequate infiltration rates and thus allow appropriate amounts of irrigation water to be used (Meek et al., 1992). Responses of hydraulic properties to a single irrigation or a rainfall event have been studied by Murphy et al. (1993) and Somaratne and Smettem (1993).

The effects of tillage systems on soil water movement are inconsistent. Some researchers have reported a higher infiltration rate for MT or RT and NT compared to CT treatments (Chan and Heenan, 1993; Logsdon et al., 1993; McGarry et al., 2000; Moreno et al., 1997; Vervoort et al., 2001), while others have found lower (Lindstrom et al., 1984; Miller et al., 1998) or similar (Gómez et al., 1999; Sauer et al., 1990) values. The higher infiltration rates under NT treatments have been related to a greater number of macropores (Logsdon et al., 1990), increased fauna activity and the litter of residues formed by accumulated OM (Logsdon and Kaspar, 1995), while higher values of
hydraulic conductivity under reduced or minimum tillage have been related to a
different pore size distribution in the surface layer rather than to changes in total
porosity (Moreno et al., 1997). Although Pikul and Aase (2003) showed that infiltration
was consistently greater under subsoiling (0.3 m depth), compared to CT plots with no
subsoiling, the benefits of subsoiling were not obvious. It has been reported that 3 to 18
years after converting from conventional to reduced tillage with cultivator or NT
agriculture on loam soils, the saturated hydraulic conductivity was lower or at least
comparable under NT than RT and CT agriculture (Lipiec et al., 2006; Singh and Malhi,
2006; Wienhold and Tanaka, 2000). On the other hand, Liebig et al. (2004) reported that
after 15 years of NT agriculture on a silt loam soil in the Great Plains, saturated hydraulic
conductivity was higher than under CT agriculture.

Kribaa et al. (2001) showed that tillage increased hydraulic conductivity,
especially at pressure heads close to saturation. Many researchers have reported that
saturated hydraulic conductivity and unsaturated hydraulic conductivity were
significantly and positively affected by zero tillage owing to either greater continuity of
pores (Benjamin, 1993) or to water flow through a very few large pores (Allmaras et al.,
1977; Angulo-Jaramillo et al., 1997; Cameira et al., 2003; Reynolds et al., 1995; Sauer et
al., 1990) or greater depth of pore system (Ehlers, 1977).

In spite of the large number of field studies conducted to evaluate tillage effects
on the hydraulic functioning of structured soils, the information available in the
literature about short-term, tillage-induced effects on the hydrophysical properties of
agricultural soils and their dynamics is very scarce (Green et al., 2003). The studies on
this subject have shown inconsistent results regarding soil physical and hydraulic properties under different tillage systems due to the transitory nature of soil structure after tillage, site history, initial and final water content, the time of sampling and the extent of soil disturbances (Azooz and Arshad, 1996). Generally, under tillage systems that include plowing, the hydraulic conductivity increases upon tillage and then decreases during the growing season due to the settling of the soil structure created by tillage (Angulo-Jaramillo et al., 1997; Azevedo et al., 1998; Bormann and Klaassen, 2008). The structural changes in recently tilled soils are caused by precipitation (Green et al., 2003) and associated wetting and drying cycles and biological activity thus leading to a decrease in hydraulic conductivity (Cameira et al., 2003; Petersen et al., 2008; Schwartz et al., 2003), which can be attributed to a reduction in the fraction of conductive mesopores (Messing and Jarvis, 1993) in conjunction with a concomitant increase in bulk density (Mellis et al., 1996).

Even considering the typical observations discussed above, the comparison of hydraulic conductivity values under conventional and conservation tillage shows many contradictory results (Arshad et al., 1999; Heard et al., 1988) and results can also be conflicting if measurements are done at the beginning or at the end of the growing season (Lampurlanés and Cantero-Martínez, 2006). These contradictory results may be partly explained by the high spatial variability of soil hydraulic properties, which may overshadow the seasonal dynamics of these soil properties (Bormann and Klaassen, 2008). A review by Green et al. (2003) has made clear that further research is needed to improve current knowledge of the influence of tillage on the soil hydrophysical
properties of freshly tilled soils. Moreover, Logsdon et al. (1993) and Strudley et al. (2008) stressed the need for studies of irrigation or rainfall effects on recently tilled soil hydraulic properties.

1.3 Concluding Statement and Foreword to Thesis

There have been many studies on the impact of tillage practices on soil physical properties, while fewer have been conducted on influence of different irrigation systems on the same soil properties. Studies that have investigated the combination of tillage and irrigation are even fewer. Adding a change in crop from wheat to maize while retaining the same tillage and irrigation systems over two growing seasons makes this study on temporal variability on selected soil properties unique and innovative. Considering the background information given above, the objectives of this thesis are:

1. To measure the effects of different tillage practices and irrigation techniques on soil physical and hydraulic properties during wheat and maize crop seasons.

2. To compare the temporal changes in soil hydraulic properties after tillage and in response to irrigation between wheat and maize crops grown in successive cropping seasons on the same experimental plots.

The rest of the thesis is divided into four chapters. Chapters 2 and 3 were written as separate papers and present findings on effects of three tillage and two irrigation methods on selected soil physical and hydraulic properties under wheat and maize crops, respectively. To avoid redundancy with chapter 1, the literature reviews included in the introductions to these Chapters are very brief and to the point. However, some
redundancy still exists as the experiments have many commonalities. Chapter 4 then assimilates and compares results between these two cropping seasons. Finally, Chapter 5 presents overall thesis conclusions and suggestions for future research.

1.4 References


Chapter 2

Temporal variability of soil physical and hydraulic properties under different tillage and irrigation management in wheat

2.1 Abstract

An experiment was conducted on wheat to investigate the effect of three tillage practices (Cultivator, Moldboard plow and Chisel plow) and two irrigation techniques (Flood and Sprinkler) on soil physical properties and temporal variations in soil hydraulic properties. Moldboard plow resulted in significantly higher grain and straw yield followed by chisel plow and cultivator, while irrigation techniques did not have a significant effect on yield. Soil volumetric water content ($\theta_v$) dynamics monitored hourly showed that there were abrupt increases in $\theta_v$ followed by decreases in response to irrigations and rain events initially in the growth period. Moldboard plow had the highest $\theta_v$ after flood irrigation and it also drained quicker than chisel plow and cultivator at 10 cm. Rain events after the irrigations showed higher increases in $\theta_v$ at this depth for sprinkler irrigated plots until the end of the cropping season. Soil bulk density ($\rho_b$), as determined from the core samples taken before irrigations, increased with soil depth, resulting in a decrease in soil total porosity ($\varphi$) with lower magnitude in cultivator and chisel plow than moldboard plow. Moldboard plow had the lowest $\theta_v$ at higher matric pressures (−30 and −100 kPa) than chisel plow and cultivator at 10 and 20 cm depths. Cultivator had significantly higher plant available water capacity ($\theta_{PAWC}$) at
10 and 20 cm depths followed by chisel and moldboard plow. Irrigation techniques did not significantly affect \( \theta_{PAWC} \). Moldboard plow had the highest volume of transmission pores (> 10 \( \mu \)m) at 10 and 20 cm depths followed by chisel plow and cultivator. Field saturated hydraulic conductivity (\( K_{fs} \)) determined before irrigation and at the end of crop season decreased significantly. Moldboard plow had the highest \( K_{fs} \) at both times. Sprinkler irrigation treatments had significantly higher \( K_{fs} \) than those of flood irrigation. The results highlight that tillage systems change soil physical and hydraulic properties depending on their type and depth. Rain events and irrigation techniques revert these changes according to their mode of application. Soil hydraulic properties may be optimized with the combination of suitable tillage and irrigation for efficient utilization of water resources.

### 2.2 Introduction

Agricultural management practices are applied as events with their transient effects realized over different time scales. The resulting variability in soil physical and hydraulic properties is dynamic in space and time. These soil properties are expected to vary even during a crop cycle especially after tillage and irrigation or rain. Logsdon et al. (1993) concluded that within-season changes in infiltration rates could be greater than the management-induced differences and suggested that the rate measurements should be recorded soon after tillage and irrigation or rainfall events. More recently, Bamberg et al. (2011) documented that high levels of soil water content after irrigation events followed by drier soil conditions resulting from large rates of evapotranspiration
caused modifications of soil physical and hydraulic properties throughout the crop production season.

Tillage and irrigation are the most influential soil manipulations having short-term effects on soil physical and hydraulic properties. Tillage leads to soil loosening depending upon the soil type, soil water content and the type of tillage operation. Changes in soil physical and hydraulic properties due to tillage are reverted back to the original state as a result of natural reconsolidation due to wetting and drying cycles (Green et al., 2003) created by rain events or supplementary irrigation provided to the crops. The reconsolidation is a dynamic process and it may depend on the frequency (Cameira et al., 2003), amount (Bandaranayake and Arshad, 2006) and method (Bandaranayake et al., 1998) of water application and subsequent drying. Consequently, the coupled effects of tillage and irrigation management are responsible for temporal variability in soil physical and hydraulic properties and processes. There are many studies in the literature highlighting the long-term effects of tillage on soil physical and hydraulic properties but less work is available on short-term (seasonal) effects. Secondly, very limited information is available on the dynamics of the temporal effects of irrigation on soil physical and hydraulic properties (Mubarak et al., 2009a; Mubarak et al., 2009b) especially when coupled with tillage management.

The type of crop can affect soil water distributions and soil hydraulic properties either directly by root water uptake (Feddes et al., 1988; Zhuang et al., 2001) or indirectly by modifying the soil pore structure through the growing root system (Angers and Caron, 1998; Kodešová et al., 2006; Rasse et al., 2000). The crop plants varying in
root systems and water requirements may affect soil physical and hydraulic properties differently. Cereal crops develop either concentrated or scattered type of root system depending on the angle of growth of lateral roots. Wheat has a concentrated type of root system with a greater number of nodal roots densely distributed (Grzesiak, 2009). This experiment was conducted with an objective to determine the effect of tillage practices and irrigation techniques on seasonal temporal variability of soil water content and physico-hydraulic properties under wheat.

2.3 Materials and Methods

The experiment was conducted during 2009-2010 to investigate the effect of different tillage and irrigation techniques on temporal variability of soil physical and hydraulic properties in wheat at the experimental area of National Agricultural Research Centre (NARC), Islamabad, Pakistan (33° 40´ 18” N, 73° 7´ 38” E, 518 m above sea level).

The soil has been mapped as Shujabad loam series (Fine-loamy, mixed, hyperthermic Udic Ustochrept) by Soil Survey of Pakistan (Khanzada, 1976) consisting of deep, imperfectly drained, calcareous, moderately fine textured, nearly level, sub-recent floodplain of the Korang River developed by mixed alluvium derived from Murree Formation of the Himalayas. The A₀ horizon (12 cm thick) ranges from brown to dark brown (10YR 4/2, 4/3) when moist, from silt loam or loam to clay loam (22 % sand, 59 % silt and 19 % clay) and from massive to weak granular with pH of 7.65 and 0.55 % organic matter. It has a cambic B horizon (148 cm thick) ranging from brown through dark brown to reddish brown (5YR-10YR 4/3, 5/3, 5/4) when moist, from clay loam to
silty clay loam (22-29 % sand, 44-55 % silt and 23-24 % clay), from weak medium to very weak very coarse sub-angular blocky with pH of 7.55-7.72 and 0.41-0.51 % organic matter. According to land capability classification, the soils have been mapped under very good irrigable land well suited to wheat, maize, pearl millet, Egyptian clover, vegetables, pulses, guava, loquat and moderately suited to sugarcane, sorghum, mustards, citrus and pears (Khanzada, 1976).

Climate of the planting site is sub-humid, sub-tropical continental type with an annual rainfall of about 1000 mm, occurring in a bi-modal pattern mostly in late summer and winter spring periods. About 60 to 70% of total rainfall is generally received during monsoons (mid-June to mid-September). Monsoon rains usually occur in heavy downpours and are accompanied by thunderstorms. The remaining rainfall is received in the winter, mostly during December-March. June and July are the hottest months having mean maximum temperature ranging from 36 to 42°C, with extremes sometimes as high as 48°C. December and January are the coldest months with mean temperature of about 3 to 3.5°C. Occasionally, the minimum temperature may drop to −3.3°C (Nizami et al., 2004). Frost occurs from mid-December to February during the days of favourable conditions, i.e., clear sky, calm wind and air temperature close to or below the freezing point. The requirement of irrigation for crop production varies every year depending on the amount and pattern of rains. Figure 2.1 shows rainfall and temperature data for the study growing season.
Figure 2.1: Daily rainfall and maximum and minimum air temperatures recorded during the wheat growing season (2009-10) at a meteorological station located approximately 1 km (aerial distance) from the experimental field.

2.3.1 Experimental Layout and Treatments

The experimental field belongs to the Maize, Sorghum and Millet Program, Crop Sciences Institute, NARC. It has previously been used for breeding and multiplying seeds of respective crops. The experiment was laid out in a split block design with four replications. Three tillage methods randomized along East-West strips (22 m long) comprised cultivator (nine tines in two rows 25 cm apart), moldboard plow (two reversible tines in two rows 30 cm apart) and chisel plow (nine tines in two rows 25 cm apart). Two irrigation techniques randomized along North-South strips (27.75 m long) consisted of flood irrigation and sprinkler irrigation. The resulting treatment combinations of tillage and irrigation were as follows:
1. Cultivator + Flood Irrigation
2. Moldboard Plow + Flood Irrigation
3. Chisel Plow + Flood Irrigation
4. Cultivator + Sprinkler Irrigation
5. Moldboard Plow + Sprinkler Irrigation
6. Chisel Plow + Sprinkler Irrigation

An untilled field was not available at the premises of NARC at the time of the experiment so three types of tillage practices varying in tillage depth and soil manipulation were used instead of a no-till control. The plot size for every combination of tillage and irrigation was 93.5 m² (8.5 m × 11 m). A layout plan of the experiment is presented in Figure 2.2.

Flood irrigation (7.5 cm water depth) was applied to the whole experimental field prior to planting in the second week of December 2009 followed by tillage operations and sowing at proper moisture level in the last week of December 2009. One pass each of moldboard plow (up to 25 cm soil depth), chisel plow (up to 15 cm soil depth) and cultivator (up to 10 cm soil depth) was applied to the respective treatments according to the layout plan (Figure 2.2). Afterwards, one pass of disk harrow was applied throughout the whole experimental field followed by two passes of cultivator carrying a traditional wooden log to level the soil surface. The implements were drawn with a 75 hp tractor. Half of the recommended dose of N (60 kg ha⁻¹) as urea and full recommended doses of P (100 kg ha⁻¹) as triple superphosphate and K (75 kg ha⁻¹) as sulphate of potash were surface applied, before the final pass of cultivator, as a basal
dose of fertilizers. Wheat (*Triticum aestivum* L. variety: Wafaq-2001) was seeded (160 kg ha\(^{-1}\) \(\approx\) 400 seeds m\(^{-2}\)) with a drill at a row to row distance of 25 cm. The second half of nitrogen fertilizer was top dressed 60 days after germination. Irrigation water channels and plot boundaries were constructed according to the layout plan (Figure 2.2). The crop was harvested manually from the whole plots in the second week of May 2010 and yield data were extrapolated to hectare basis.

### 2.3.2 Irrigation Techniques

Flood irrigation was applied to the respective plots as basin irrigation using a gravity flow system. Complete perimeter dikes were made around all the plots to prevent any runoff from the plot or leakage to the adjacent plots. Irrigation water was allowed to enter the plots manually by cutting off the dikes at two places from the water channel dispensing the respective plot for increasing uniformity of application. A cut-throat flume (10 cm \(\times\) 90 cm) was fixed in the main water channel (Figure 2.2) supplying water to the whole experimental area to monitor the flow of water to the field. The flood irrigation (7.5 cm depth of water) was applied to the respective plots in the second week of April 2010. The time \(t\) needed for the irrigation per plot was calculated from the relation:

\[
t = \frac{a \times d}{Q_f}\]

(1)
Figure 2.2: Layout plan of the experiment and sprinkler irrigation design. Stippled area is two-stage footprint of rain-gun sprinkler. B₁, B₂, B₃ and B₄ are the blocks 1, 2, 3 and 4, respectively. Lined strips are water channels and grey strips are uncultivated paths.
where $a$ is the area ($L^2$) of the plot, $d$ is the depth ($L$) of irrigation and $Q_f$ is the free flow discharge rate ($L^3 \ T^{-1}$) through the water channel. The $Q_f$ was calculated from the relation:

$$Q_f = C_f h_u^{n_f}$$  \hspace{1cm} (2)

where $C_f$ is free-flow coefficient ($L^{(3-n_f)T^{-1}}$), $n_f$ is the free-flow exponent (dimensionless) and $h_u$ is upstream flow depth ($L$) determined from the flume scale. The $C_f$ and $n_f$ were taken as 1.404 and 1.840, respectively (Federal Water Management Cell, 1996) and $h_u$ was kept at 0.52 ft throughout the irrigation process.

Sprinkler irrigation (5 cm depth of water) was applied to the respective plots two days after the flood irrigation by a movable rain-gun sprinkler system (Courtesy: Water Resources Research Institute (WRRI), NARC, Islamabad, Pakistan). The depth of water applied was less than the flood irrigation according to the reported saving of water (30%) with sprinkler irrigation bearing similar yield (Haq, 1990). A high pressure multistage pump coupled with a 16 hp diesel engine was mounted on a two wheel trolley and towed to the experimental field. The sprinkler was mounted on a tripod riser stand (1.34 m above the ground) and moved through the experimental field as required. Rain-gun model PY1-30 equipped with a 12 mm nozzle was set at a trajectory angle of 30°. It is able to give a discharge of 2.35 dm$^{-3} \ s^{-1}$ throwing 3.65 mm h$^{-1}$ of water to dispense a radius of 27.2 m when a working pressure head of 30 m is applied (Ahmad, 2001). The Christiansen’s coefficient of uniformity (Christiansen, 1942) of the rain gun, adopted as a
measure of uniformity of distribution of water, is 88.1% (Yasin et al., 2000). The average wind speed on the day when sprinkler irrigation was done was 2.38 km h$^{-1}$. The suction side of the pump was coupled to a reinforced, corrugated rubber hose (6.5 cm internal diameter). The other end of the hose was fastened with a check valve and dipped into a nearby concrete lined surface water ditch. The flow of water in the ditch was maintained to match the discharge from the rain-gun. The delivery side of the pump was attached with a canvas hose (5 cm internal diameter) to convey water to the rain gun. The engine throttle was controlled to attain the working pressure suitable for the radius of coverage to match with the entire strip of sprinkler irrigated plots in a replication. The rotary rain gun sprinkler is also able to move in a sector. This feature was used to apply the sprinkler irrigation to cover a rectangular field in two steps as shown in Figure 2.2. The spray beyond the treatment plots dropped in the non-experimental areas. It was collected in the water ditches as surplus and carried out of the field. A graduated catch can was placed in the centre of the area covered by sprinkler irrigation to measure the depth of water.

2.3.3 Monitoring Soil Water Content and Soil Temperature

The $\theta_v$ (L$^3$ L$^{-3}$) was monitored indirectly using water content reflectometer (WCR) model CS616 manufactured by Campbell Scientific Inc. (Logan, UT, USA). A total of 12 pits (50 cm wide, 50 cm long and 30 cm deep) were dug by hand, in the last week of February 2010, one in every treatment combination in two of the four replication blocks. The pits were located at the centre of the plot with respect to longitudinal
boundaries but 2 m away from the widthwise boundary closer to the datalogger. The WCR probes were manually inserted horizontally at 10 and 20 cm depths stacked vertically, keeping the rods as close to parallel as possible to maintain the design wave guide geometry and avoiding air voids around the rods.

The CS616 WCR consists of two stainless steel rods connected to a printed circuit board encapsulated in epoxy. The rods are 300 mm long, 3.2 mm in diameter and have a center-to-center spacing of 32 mm. An electromagnetic square wave is generated in the circuit board and propagated along the parallel rods acting as waveguides. The signal is reflected from the end of the rods and travels back to the circuit board, which detects the returning signal and oscillates another electromagnetic wave down the rods. The travel time period of the signal on the probe rods depends on the dielectric permittivity of the soil monitored. As soil water content changes, the resultant dielectric property change causes a shift in the oscillation frequency of the circuit. The output from WCR is a time period which is inversely related to the oscillation frequency. It ranges from 14 μS with rods in air to about 42 μS with the rods completely immersed in water. The CS616 WCR has an accuracy of 2.5% at bulk electrical conductivity ≤ 0.5 dS m\(^{-1}\) and bulk density ≤ 1.55 Mg m\(^{-3}\) with both resolution and precision of 0.1% in the measurement range of 0-50 % \(\theta_v\) (Campbell Scientific Inc., 2011).

The calibration of CS616 (to convert the output time period to \(\theta_v\)) depends mainly on soil particle size distribution (Rüdiger et al., 2010). The \(\theta_v\) was calculated using the calibration equation developed for a soil at University of Guelph’s Elora
Research Station (Kulasekera et al., 2011) similar in particle size distribution to the soil used for the experiment:

\[ \theta_v = 0.0008\tau^2 - 0.168\tau + 0.0609 \]  

(3)

where \( \tau \) is the WCR output time period (μs). The WCRs were connected to a datalogger (Model CR1000 manufactured by Campbell Scientific Inc., Logan, UT, USA) fixed in the centre of the two replication blocks selected for WCR probes. The WCR period was determined every ten minutes and an average for one hour was stored in the datalogger’s memory. The WCR readings were also taken with each probe held in the air to determine inter-probe variations at effectively zero water content following the recommendations by Seyfried and Murdock (2001).

Soil temperature (°C) was also monitored from the same pits described above with type-T (Copper-Constantan) thermocouples made in the lab by soldering one end of the copper-constantan wire, insulating with rubber tubing and transparent silicone sealant and encapsulating with a small piece of copper pipe. The thermocouples were installed at the same depth as WCRs but at a distance of 20 cm from them. A hole (1 cm diameter and 15 cm long) was made horizontally parallel to the WCR probes with the help of an auger so that the thermocouples were installed at the midpoint of the zone of measurement of WCRs. The thermocouples were then inserted in the holes and the holes were packed by pressing a stone-free paste of the local soil into them to make a good thermal contact between the thermocouples and the soil. The thermocouples were connected to a relay multiplexer model AM16/32B manufactured by Campbell Scientific Inc. (Logan, UT, USA) with an on-board temperature reference used as an
interface between the datalogger and the thermocouples. The time interval of soil temperature measurements was kept the same as that for $\theta_v$ to do a temperature correction of WCR output time period (Campbell Scientific Inc., 2011). The pits were backfilled with their own soils tamping manually to approximately the original bulk density.

2.3.4 Monitoring Soil Water Potential

Total pore water potential ($\psi_m$) was measured by tensiometers installed, in the second week of March 2010, at the same depths as WCRs and thermocouples. Tensiometers were made of polyvinyl chloride (PVC) pipe (16 mm internal diameter and 21.5 mm external diameter) with a glass tube (12.5 mm internal diameter) fitted inside, and protruding 5 cm out of, the PVC pipe at one end (with a removable rubber septum seal inserted at the top) and a 5.5 cm porous ceramic cup at the other end. A 26 cm long tensiometer was used for the upper depth (10 cm) and a 41 cm long tensiometer was used for the lower depth (20 cm). The installation was made in such a way that the centre of the ceramic cup was placed at the desired depths. A vertical hole was bored accordingly using an auger with the same outside diameter as the tensiometer to fit without a gap between the porous cup and surrounding soil. The walls of the hole were wetted with water using a squeeze bottle and the prehydrated tensiometer was slipped into it carefully until it stopped at the end of the hole ensuring a good hydraulic contact between the ceramic cup and the soil at the bottom. A handheld digital Tensimeter with a hypodermic needle and a battery-operated pressure transducer (Soil Measurement
Systems, Las Cruces, NM, USA) was used to measure the partial vacuum above the
water in the tensiometer tube twice in a week, i.e., Mondays at 1500 h and Fridays at
0900 h.

2.3.5 Determination of Saturated Hydraulic Conductivity

The Guelph Pressure Infiltrometer (GPI) attachment to the Guelph Permeameter
(GP) reservoir (Soil Moisture Equipment Corp., Santa Barbara, CA, USA) was used to
measure steady state infiltration rate ($L^3 T^{-1}$) at three places from all treatment
combinations in two replications. The measurements were carried out in 4th week of
March 2010 and 3rd week of May 2010, i.e., 13 weeks and 21 weeks after tillage
operations, respectively. A level surface was prepared at each site by scraping off the
top 1-2 cm of soil with a hand trowel and the GPI attachment was placed vertically onto
the soil surface. A wooden block was put on the attachment and struck with a hammer
to get the desired insertion depth keeping it as vertical as possible. The internal
diameter of GPI ring was 9.6 cm and it was inserted to a depth of 4.5 cm. After installing
the GPI attachment, the GP reservoir was fitted onto it carefully. The infiltration
measurements were taken at a single ponding depth of 10 cm. The inner reservoir was
used to get better resolution because it was a relatively slow infiltration rate. The
outflow readings were taken at a 5-minute interval and recorded until the initial
transient flow approached a steady state. The soil had a lot of interconnected cracks
often resulting in the flow of water coming out from a nearby crack causing the
measurements to fail. Therefore, the GPI had to be installed at different locations in
each plot to make it successful. The $K_{fs}$ was calculated from the quasi-steady flow rate out of the cylinder (W. D. Reynolds, 2008a) taking the value of macroscopic capillary length parameter ($\alpha^*$) as $0.12 \text{ cm}^{-1}$ which is appropriate for agricultural soils (W. D. Reynolds, 2008b).

2.3.6 Determination of Soil Water Retention Characteristics and Bulk Density

Intact soil cores were collected from all treatment plots in two replications in the 1st week of April 2010. The cores were obtained from the same two depths (10 and 20 cm) as for other determinations and additionally from 30 cm depth in such a way that the centre of the core falls at the required soil depth. A small pit (30 cm × 30 cm) was dug in the centre of every plot and a level bed was made accordingly. Two stainless steel core cylinders of 5 cm internal diameter and 2.5 cm length with wall thickness of 0.5 mm and a beveled cutting head at the bottom were placed side by side on the level bed surface and hammer driven into the soil using a wooden tool with 1 m long handle (keeping as vertical as possible) leaving approximately 5 mm at the top of the cylinder. A similar core cylinder without a beveled head was then placed over that cylinder and driven carefully until about 1 mm extra soil protruded out of the cylinder. The soil below the bottom of the cylinder was cut off carefully to remove the core cylinder. The extra soil from the ends was trimmed smooth and flush with the cylinder. The core samples were wrapped in polythene paper and brought to the laboratory.

Soil water retention ($\theta_v(\psi_m)$) was determined at $-30 \ (\psi_{FC}), \ -100 \ (\psi_{100}), \ -500 \ (\psi_{500}), \ -1000 \ (\psi_{1000})$ and $-1500 \ (\psi_{PWP})$ kPa of $\psi_m$ using pressure-plate extractors
(Soilmoisture Equipment Corp., Santa Barbara, CA, USA). Soil core samples placed on pre-saturated porous ceramic plates with the appropriate bubbling pressure were satiated with deaired tap water and equilibrated with the desired air pressures in the pressure chambers. Water content was determined gravimetrically and converted to $\theta_v$ at each $\psi_m$ (W.D. Reynolds and Topp, 2008). The soil core samples, after determining $\theta_v$ at all $\psi_m$, were oven dried at 105°C to determine the $\rho_b$ and calculate $\phi$. The $\theta_{PAWC}$ was calculated as the difference in $\theta_v$ retained between $\psi_{FC}$ and $\psi_{PWP}$, $\theta_{FC}$ and $\theta_{PWP}$, respectively (Romano and Santini, 2002). Volume of soil occupied by pores of various diameter classes (<0.2 μm ($\phi_{<0.2}$), 0.2-0.3 μm ($\phi_{0.2-0.3}$), 0.3-0.6 μm ($\phi_{0.3-0.6}$), 0.6-3 μm ($\phi_{0.6-3}$), 3-10 μm ($\phi_{3-10}$) and >10 μm ($\phi_{>10}$)) was computed from $\theta_v(\psi_m)$ data assuming soil pores to be cylindrical and contact angle of water to the capillary pores as zero (Flint and Flint, 2002).

2.3.7 Statistical Analysis

2.3.7.1 Temporal Stability of Soil Water Content

The $\theta_v$ data regarding were subject to temporal stability analysis first defined by Vachaud et al. (1985) as time invariant association between spatial location and classical statistical parametric values. This concept was later applied by Martínez-Fernández and Ceballos (2003), Martínez-Fernández and Ceballos (2005), Starks et al. (2006), Heathman et al. (2009), Zhao et al. (2010) and Kulasekera et al. (2011). Guber et al. (2008), and later Hu et al. (2010), used the concept for temporal measurements of soil water content taken at different depths. The concept was used to evaluate temporal
persistence of the relative differences in soil water content and their stability as affected by different soil management practices applied in the experimental field. The analysis was conducted for two time periods, i.e. before and after irrigation events. The number of hourly observations recorded for flood and sprinkler irrigations were not equal because they were applied at different days resulting in separate analysis for both irrigation techniques. Replication-averaged measurements for three tillage treatments (taken as plots) and two depths were evaluated. Time averaged relative difference ($\bar{\delta}_{ij}$) of soil water content for every monitoring plot $i$ at each depth $j$ identified whether a plot was wetter or drier compared to the other plots regardless of the observation time calculated from

$$\bar{\delta}_{ij} = \frac{1}{m} \sum_{k=1}^{m} \delta_{ijk}$$

(4)

and its standard deviation ($\sigma(\bar{\delta}_{ij})$) indicated the stability of soil water content with time calculated from

$$\sigma(\bar{\delta}_{ij}) = \left( \frac{1}{m-1} \sum_{k=1}^{m} (\delta_{ijk} - \bar{\delta}_{ij})^2 \right)^{1/2}$$

(5)

where $\delta_{ijk}$ is the relative difference in soil water content at plot $i$ at depth $j$ and time $k$ calculated from

$$\delta_{ijk} = \frac{\theta_{ijk} - \bar{\theta}_{jk}}{\bar{\theta}_{jk}}$$

(6)
\( \theta_{ijk} \) is the individual measurement of soil water content at plot \( i \) at depth \( j \) and time \( k \), \( m \) is the number of times the measurement was taken and \( n \) is the number of plots and \( \bar{\theta}_{jk} \) is the hourly average of soil water content at depth \( j \) and measurement time \( k \) calculated from

\[
\bar{\theta}_{jk} = \frac{1}{n} \sum_{i=1}^{n} \theta_{ijk}
\]

(7)

The plots with higher \( \bar{\delta}_{ij} \) indicated higher water content over time and those with lower \( \sigma(\bar{\delta}_{ij}) \) were considered to be temporally more stable (Hu et al., 2010). The means were not ranked due to lesser number of treatment plots compared and the interest in relative temporal wetness of the tillage treatments at both depths.

2.3.7.2 Analysis of Variance

Variance analyses were performed with SAS software version 9.1 (SAS Institute Inc., Cary, NC, USA) using Proc Mixed model. The data parameters determined were handled differently depending on their structure. Block, tillage and irrigation were taken as classification variables for all parameters. Non-randomized repeated measures were included as classification variables for the respective parameters (Depth for bulk density, total porosity, soil water potential, soil water retention and pore size distribution; Time for field saturated hydraulic conductivity and soil water potential; Pressure heads for soil water retention; and Pore classes for pore size distribution). The covariance structure of autoregressive order 1 (ar1) was used for one repeated measure and a crossed unstructured × compound symmetric (un@cs) for two repeated
measures. F-tests were used as test of significance at error rate ($\alpha$) of 0.05 for all analyses. Least square means and standard error of means were obtained and all pairwise means comparisons were made using Tukey’s multiple means adjustment.

The assumptions for the analysis were that the fixed effects, repeated measures and their interactions are additive and independent, and that experimental errors are random, independently and normally distributed about zero mean, and with a common variance (Bowley, 2008). Residual analyses were performed to test the validity of the assumptions. Internal studentized residuals were computed and Lund’s test of studentized residuals was used to identify outliers (Lund, 1975). Mean of the residuals and Shapiro-Wilk W statistic was computed to confirm the normality of the residuals.

2.4 Results and Discussion

2.4.1 Grain and Straw Yield

The tillage practices affected the grain ($P = 0.0331$) and straw ($P = 0.0481$) yield (Table 2.1) significantly. There was no effect of irrigation methods used on both the parameters. Moldboard plowing resulted in significantly higher grain (2685 kg ha$^{-1}$) and straw (5540 kg ha$^{-1}$) yield than cultivator. Chisel plow was not significantly different from both these cultivation methods. Moldboard and chisel plow had 14% and 5% higher grain yield, respectively and 12 and 5% higher straw yield, respectively than that of cultivator. Higher yield with moldboard plow may be attributed to better root growth and resulting water uptake (Chaudhary et al., 1985).
Table 2.1: Yield (kg ha\(^{-1}\)) parameters of wheat as affected by tillage and irrigation practices.

<table>
<thead>
<tr>
<th></th>
<th>Cultivator</th>
<th>Moldboard</th>
<th>Chisel</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Grain Yield</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flood</td>
<td>2341</td>
<td>2672</td>
<td>2489</td>
<td>2501</td>
</tr>
<tr>
<td>Sprinkler</td>
<td>2373</td>
<td>2699</td>
<td>2470</td>
<td>2514</td>
</tr>
<tr>
<td>Mean</td>
<td>2357 B</td>
<td>2685 (14) A</td>
<td>2480 (5) AB</td>
<td></td>
</tr>
<tr>
<td><strong>Straw Yield</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flood</td>
<td>4971</td>
<td>5485</td>
<td>5247</td>
<td>5234</td>
</tr>
<tr>
<td>Sprinkler</td>
<td>4920</td>
<td>5594</td>
<td>5143</td>
<td>5219</td>
</tr>
<tr>
<td>Mean</td>
<td>4945 B</td>
<td>5540 (12) A</td>
<td>5195 (5) AB</td>
<td></td>
</tr>
</tbody>
</table>

Means sharing same letters are statistically not different at \(\alpha=0.05\). Values in the parenthesis are percent increase over cultivator.

2.4.2 Soil Water Content

The dynamics of \(\theta_v\) monitored hourly for different tillage practices and irrigation techniques at 10 and 20 cm depths throughout the wheat growth period show a similar pattern for all treatments and depths (Figure 2.3). The \(\theta_v\) was higher initially in the monitoring period due to 82 mm of rain in the prior month (Figure 2.1) and less evaporation due to low temperature (average minimum of 6.4°C and average maximum of 19.5°C). The response of rainfall and irrigation events is evident by a noticeable increase in \(\theta_v\). Even a small amount of rainfall has been reflected by an increase in \(\theta_v\). Similarly, \(\theta_v\) decreased during drying periods in all cases. Both the increase and decrease responses were sharper at 10 cm depth. Generally, higher \(\theta_v\) at 20 cm depth were observed except after the rain or irrigation events. Higher diurnal variation in \(\theta_v\)
was observed in the last month of wheat season due to high soil temperature (Evett et al., 2011).

Tillage practices and irrigation techniques affected the $\theta_v$ differently. The $\theta_v$ after flood irrigation, in case of moldboard plow at 10 cm depth, went abruptly higher than chisel plow and cultivator but during the drying period after irrigation, it decreased sharply and was the lowest in about three days. The highest $\theta_v$ just after the flood irrigation corresponds to the higher total porosity due to moldboard plow (Table 2.2). The $\theta_v$ started lowering sharply after the irrigation because of the higher $K_{fs}$ (Figure 2.7) and more water conducting pores (Table 2.3). At 20 cm depth, both moldboard plow and chisel plow showed higher $\theta_v$ after flood irrigation due to their similarity in the depth of cultivation. The $\theta_v$ at this depth did not revert as sharply as at the upper depth so it took about a week to reach the $\theta_v$ of the cultivator treatment.

Sprinkler irrigation did not result in as much $\theta_v$ changes as in case of flood irrigation and the most prominent change was observed in moldboard plow at 10 cm depth but the drying trend was similar as for flood irrigation. Sprinkler irrigation did not create field-saturated conditions resulting in lower $\theta_v$ after irrigation. High amount of rain in the second half of April and the first half of May, 2010 resulted in higher $\theta_v$ for all tillage and irrigation treatments at both depths. At this time, when the wheat crop was close to maturity with lower water requirements, $\theta_v$ did not drop during the drying periods though the daily maximum temperature was rising.
Figure 2.3: Temporal soil water content ($\theta_v$) as affected by different tillage and irrigation management practices at two depths in wheat.
The differences in $\theta_v$ for different tillage treatments at 20 cm depth were observed in sprinkler irrigation but not in flood irrigation. Moldboard plow and chisel plow showed higher $\theta_v$ than that of the cultivator even at this stage. The $\theta_v$ at 10 cm depth was also higher in sprinkler than the flood irrigation treatments for all tillage types by the end of the cropping season. This gives evidence of the fact that reconsolidation after tillage (Green et al., 2003) is lower in the case of sprinkler irrigation resulting in more water retention, which is similar for all tillage treatments at 10 cm but more for moldboard plow and chisel plow than cultivator at 20 cm depth.

The results regarding average inter-temporal relative difference ($\bar{\delta}_{ij}$) and standard deviation ($\sigma(\bar{\delta}_{ij})$) of $\theta_v$ for different tillage practices and irrigation techniques at two depths before and after irrigation events (Figure 2.4) show that the $\theta_v$ was temporally less stable after irrigation especially in the flood irrigation. A comparison among the measurement depths revealed that the lower depth was more stable in $\theta_v$ temporally than the upper one for all tillage and irrigation treatments before and after irrigation. The $\theta_v$ in moldboard plow was more stable when flood irrigation was applied.

Spatial patterns of the temporal $\theta_v$ revealed that the cultivator plots at 10 cm depth were less prone to the flood irrigation. They were temporally drier before irrigations and remained drier after flood irrigation while they remained wetter after sprinkler irrigation (Figure 2.4) whereas the reverse was observed for moldboard plow and chisel plow plots. This could be related to more preferential flow in case of cultivator after flood irrigation whereas sprinkler irrigation being less likely responsible
for preferential flow. Almost no change was observed in the spatial patterns of $\theta_v$ at 20 cm depth.

Figure 2.4: Time averaged relative difference ($\bar{\delta}_{ij}$) of soil water content as affected by different tillage and irrigation management practices at two depths in wheat. Error bars represent the standard deviation ($\sigma(\bar{\delta}_{ij})$).

2.4.3 Soil Temperature

Temporal variations of soil temperature (°C) under different tillage practices and irrigation techniques at two depths during the wheat crop season are presented in Figure 2.5. Soil temperature had a rising trend throughout the season in all cases.
Figure 2.5: Temporal changes in soil temperature at two depths as affected by different tillage and irrigation management practices in wheat.
Diurnal fluctuations were more pronounced at 10 cm depth, which tended to increase towards the end of the season. Soil temperature did not seem to be related to irrigation techniques or rain events; rather to the variations of atmospheric temperature (Figure 2.1). The trends related to soil temperature variations were similar for all tillage practices and irrigation techniques.

Temporal stability analysis (Appendix I) revealed that the spatial patterns of soil temperature were very stable. Higher time averaged relative differences were observed for cultivator and chisel plow with flood irrigation, whereas for moldboard plow with sprinkler irrigation.

2.4.4 Soil Bulk Density and Total Porosity

The $\rho_b$ and consequent $\varphi$ as affected by tillage and irrigation at three depths determined in the middle of the growing season before irrigation events are shown in Table 2.2. Variance analysis show a significant interaction between tillage practices and depths ($P = 0.0369$). Moldboard plow had significantly lower $\rho_b$ (1.30 Mg m$^{-3}$) at 10 cm than that of cultivator (1.40 Mg m$^{-3}$) with chisel plow being in between (1.37 Mg m$^{-3}$) was not different from either of them. At lower soil depth (20 cm), the $\rho_b$ was significantly lower with moldboard plow (1.34 Mg m$^{-3}$) than with both the other tillage treatments, which were not different with each other. This resulted in a lower difference in $\rho_b$ between the two depths with moldboard plow and a greater difference with other tillage types.
Table 2.2: Bulk density ($\rho_b$), total porosity ($\varphi$) and plant available water capacity ($\theta_{PAWC}$) as affected by tillage and irrigation practices at three depths in wheat determined in the 1st week of April, 2010.

<table>
<thead>
<tr>
<th>Tillage</th>
<th>Irrigation</th>
<th>$\rho_b$ (Mg m$^{-3}$)</th>
<th>$\varphi$</th>
<th>$\theta_{PAWC}$ (m$^3$ m$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10 cm</td>
<td>20 cm</td>
<td>30 cm</td>
<td>10 cm</td>
</tr>
<tr>
<td>Cultivator</td>
<td>Flood</td>
<td>1.39</td>
<td>1.47</td>
<td>1.50</td>
</tr>
<tr>
<td></td>
<td>Sprinkler</td>
<td>1.41</td>
<td>1.46</td>
<td>1.51</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>1.40 b-d</td>
<td>1.47 ab</td>
<td>1.51 a</td>
</tr>
<tr>
<td>Moldboard</td>
<td>Flood</td>
<td>1.30</td>
<td>1.34</td>
<td>1.49</td>
</tr>
<tr>
<td></td>
<td>Sprinkler</td>
<td>1.30</td>
<td>1.34</td>
<td>1.50</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>1.30 e</td>
<td>1.34 de</td>
<td>1.49 a</td>
</tr>
<tr>
<td>Chisel</td>
<td>Flood</td>
<td>1.39</td>
<td>1.44</td>
<td>1.53</td>
</tr>
<tr>
<td></td>
<td>Sprinkler</td>
<td>1.36</td>
<td>1.44</td>
<td>1.51</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>1.37 c-e</td>
<td>1.44 a-c</td>
<td>1.52 a</td>
</tr>
</tbody>
</table>

Means sharing same letters are statistically not different at $\alpha = 0.05$. 
There was no difference in the $\rho_b$ of all tillage types at 30 cm depth but at 20 cm depth cultivator and chisel plow had statistically similar $\rho_b$. There was no effect of irrigation techniques on $\rho_b$ because the core sampling for water retention characteristics and $\rho_b$ was done before irrigation processes in the wheat experiment.

### 2.4.5 Soil Water Retention

The main effects of tillage and irrigation alone on $\theta_v(\psi_m)$ (Figure 2.6) were not statistically significant ($\alpha = 0.05$). The water retained at 10 and 20 cm depths was similar but significantly higher ($P = 0.0159$) than that at 30 cm depth. The average $\theta_v$ at different $\psi_m$ decreased significantly ($P < 0.0001$) with increasing pressure. The interactive effects of tillage × depth ($P < 0.0001$) and tillage × pressure ($P = 0.0014$) on $\theta_v$ were significant. Cultivator had the highest $\theta_v$ at all $\psi_m$ at 10 as well as 20 cm depths, followed by chisel plow and moldboard plow. The most noticeable differences were found at higher $\psi_m$ ($\psi_{FC}$ and $\psi_{100}$) at both depths. The lower $\psi_m$ ($\psi_{500}$, $\psi_{1000}$ and $\psi_{1500}$) had similar $\theta_v$ for all treatments.

The $\theta_v(\psi_m)$ at 30 cm depth was lower than that at the upper depths at all $\psi_m$ and no response of tillage was observed. Although the $\theta_v$ in case of chisel plow at 10 cm depth was lower than that of cultivator at higher $\psi_m$, the difference was not significant while moldboard plow had significantly lower $\theta_v$ at these pressures. Contrastingly, the water retention for chisel plow at 20 cm depth was similar but higher than the moldboard plow and significantly lower than the cultivator.
Figure 2.6: Soil water retention as affected by different tillage and irrigation management practices at three depths in wheat.

The similarity of $\theta_v(\psi_m)$ in cultivator to that of chisel plow but contrast with the moldboard plow at 10 cm depth might be related to the similarity of the first two types of tillage being different from the moldboard plow. Similarly, at 20 cm depth, the resemblance of $\theta_v(\psi_m)$ in chisel plow and moldboard plow contrasting with the cultivator might be associated with the depth of tillage in the two types being more than the cultivator.

The relationship between $\theta_v$ (from WCRs) and $\psi_m$ (from tensiometers) as observed twice a week in the field throughout the growing season is presented in Figure 2.7. The $\psi_m$ remained between −80 to −33 kPa most of the time, showing that soil matric potential persisted at the higher end of plant available water range during the
season. The $\theta_v$ was generally lower at 10 cm depth than at 20 cm depth for all tillage and irrigation treatments. This might be due to higher $\varphi_{>10}$ at 10 cm depth (Table 2.3), with soil water draining easily into 20 cm depth with lower $\varphi_{>10}$. The relationship shows a scattered pattern, probably due to overlap of many wetting and drying cycles. This may be attributed to the frequent rain events distributed over the wheat season. The trend of $\theta_v(\psi_m)$ was more typical in flood irrigated plots, especially at 10 cm depth.

### 2.4.6 Plant Available Water Capacity

The $\theta_{PAWC}$ (Table 2.2) determined in the middle of the wheat season were significantly ($P = 0.0193$) affected by the main effects of tillage treatments but not with the irrigation techniques. The $\theta_{PAWC}$ was significantly higher in cultivator than that in moldboard plow. Chisel plow had lower $\theta_{PAWC}$ than the cultivator and higher than the moldboard plow but the difference was not significant. The effect of tillage $\times$ depth interaction ($P = 0.0004$) revealed that the differences in $\theta_{PAWC}$ were significant due to tillage treatments only at 10 and 20 cm depth but not significant at 30 cm depth. Cultivator had significantly higher $\theta_{PAWC}$ at 10 and 20 cm depth followed by chisel plow and moldboard plow.
Figure 2.7: The relationship between volumetric water content ($\theta_v$) and soil matric potential ($\psi_m$) as affected by different tillage and irrigation management practices at two depths in wheat. Brown and blue points show measurements taken before and after irrigations, respectively.
2.4.7 Pore Size Distribution

A significant variation (P < 0.0001) was observed in the volume occupied by different pore diameter classes (Table 2.3). The distribution of pore sizes averaged over tillage, irrigation and depth revealed that most of the pores were <0.2 μm in diameter (pores smaller than the permanent wilting point) followed by the pores >10 μm in diameter (pores greater than the field capacity). Almost 70% of the total pores were in these classes. The effect of tillage × pore class interaction showed that tillage types significantly (P < 0.0001) affected the $\phi_{>10}$ and $\phi_{0.6-3}$. Moldboard plow had the highest $\phi_{>10}$ (0.20 m$^3$ m$^{-3}$) followed by chisel plow (0.15 m$^3$ m$^{-3}$) and cultivator (0.13 m$^3$ m$^{-3}$). The $\phi_{0.6-3}$ was significantly higher in cultivator (0.07 m$^3$ m$^{-3}$) than that in chisel plow (0.05 m$^3$ m$^{-3}$) and moldboard plow (0.04 m$^3$ m$^{-3}$). The depth × pore class interaction was also significant (P < 0.0001) showing that various pore sizes were differently distributed among the depths studied. The $\phi_{>10}$ as well as the $\phi_{<0.2}$ was significantly higher at 10 cm than those at 20 and 30 cm depths while the $\phi_{0.6-3}$ was significantly higher at 30 cm than at 10 and 20 cm depths.

The three way interaction between tillage × depth × pore class depicted that moldboard plow had significantly higher (P = 0.0001) volume of transmission pores > 10 μm at 10 cm (0.23 m$^3$ m$^{-3}$) and 20 cm (0.21 m$^3$ m$^{-3}$) than cultivator and chisel plow (Table 2.3). Chisel plow also had significantly higher $\phi_{>10}$ than the cultivator at both depths but lower than that of moldboard plow.
Table 2.3: Pore size distribution (m$^3$ m$^{-3}$) as affected by tillage and irrigation practices in three soil depths in wheat.

<table>
<thead>
<tr>
<th>Tillage</th>
<th>Irrigation</th>
<th>Pore Diameter (μm)</th>
<th>&lt; 0.2</th>
<th>0.2-0.3</th>
<th>0.3-0.6</th>
<th>0.6-3</th>
<th>3-10</th>
<th>&gt; 10</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>10 cm</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cultivator</td>
<td>Flood</td>
<td>0.187</td>
<td>0.019</td>
<td>0.042</td>
<td>0.062</td>
<td>0.029</td>
<td>0.137</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sprinkler</td>
<td>0.186</td>
<td>0.017</td>
<td>0.039</td>
<td>0.063</td>
<td>0.039</td>
<td>0.124</td>
<td></td>
</tr>
<tr>
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<td>0.186 b</td>
<td>0.018 q-u</td>
<td>0.040 l-p</td>
<td>0.063 jk</td>
<td>0.034 m-s</td>
<td>0.131 hi</td>
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<td>0.166</td>
<td>0.014</td>
<td>0.044</td>
<td>0.034</td>
<td>0.025</td>
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<tr>
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<td>0.013</td>
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<tr>
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<td>0.013 s-u</td>
<td>0.039 m-q</td>
<td>0.034 m-s</td>
<td>0.026 n-u</td>
<td>0.228 a</td>
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<td>0.038 m-q</td>
<td>0.049 k-m</td>
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<td>0.163 c-f</td>
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<td>0.020</td>
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<td>0.047</td>
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<td>0.047 k-n</td>
<td>0.063 jk</td>
<td>0.021 p-u</td>
<td>0.120 i</td>
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<tr>
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<td>0.033</td>
<td>0.024</td>
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<td>0.156 d-g</td>
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<td>0.030</td>
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<td>0.019</td>
<td>0.139</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>0.156 d-g</td>
<td>0.015 r-u</td>
<td>0.029 m-u</td>
<td>0.070 j</td>
<td>0.022 o-u</td>
<td>0.138 g-i</td>
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<tr>
<td>Moldboard</td>
<td>Flood</td>
<td>0.153</td>
<td>0.009</td>
<td>0.032</td>
<td>0.069</td>
<td>0.021</td>
<td>0.156</td>
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<tr>
<td></td>
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<td>0.009</td>
<td>0.035</td>
<td>0.057</td>
<td>0.028</td>
<td>0.148</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>0.155 e-g</td>
<td>0.009 u</td>
<td>0.033 m-s</td>
<td>0.063 jk</td>
<td>0.025 o-u</td>
<td>0.152 f-h</td>
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<tr>
<td>Chisel</td>
<td>Flood</td>
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<td>0.014</td>
<td>0.035</td>
<td>0.062</td>
<td>0.031</td>
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<tr>
<td></td>
<td>Sprinkler</td>
<td>0.153</td>
<td>0.009</td>
<td>0.051</td>
<td>0.059</td>
<td>0.033</td>
<td>0.127</td>
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<tr>
<td>Mean</td>
<td>0.155 e-g</td>
<td>0.012 tu</td>
<td>0.043 k-o</td>
<td>0.061 j-l</td>
<td>0.032 m-t</td>
<td>0.126 i</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The means in rows are tillage × depth × class means (irrigation averaged). Means sharing same letters are statistically not different at $\alpha=0.05$. 

72
The volume of pores belonging to other storage pore classes ($\varphi_{0.2-0.3}$, $\varphi_{0.3-0.6}$, $\varphi_{0.6-3}$ and $\varphi_{3-10}$) was mostly similar for different tillage practices at all depths and no trends were observed. Irrigation did not have an effect on pore size distribution because the sampling was done before each irrigation event.

2.4.8 Field Saturated Hydraulic Conductivity

Tillage practices significantly affected ($P = 0.0064$) the $K_{fs}$. Moldboard plow had significantly higher $K_{fs}$ (1.06 cm h$^{-1}$) than chisel plow and cultivator (Figure 2.8). The conductivity decreased significantly ($P = 0.0319$) with $K_{fs}$ at 13 WAT greater than that at 21 WAT. Although, the main effect of irrigation was not significant but the irrigation \times time interaction revealed that there was a significant ($P = 0.0019$) change in the $K_{fs}$ due to irrigation techniques. At 13 WAT the $K_{fs}$ was similar with flood and sprinkler irrigation. As the $K_{fs}$ at 13 WAT was determined before irrigation and that at 21 WAT after irrigation, the lowering effect was more pronounced with flood irrigation than with sprinkler irrigation at 21 WAT. This might be due to more reconsolidation of soil with flood irrigation than with sprinkler irrigation. The three-way interactive effects of tillage \times irrigation \times time indicated that the most noticeable decrease was observed when flood irrigation was done after moldboard plowing ($K_{fs}$ of 1.30 to 0.72 cm h$^{-1}$ from 13 to 21 WAT, respectively) and the least noticeable decrease was displayed when sprinkler irrigation was practiced after cultivator ($K_{fs}$ of 0.79 to 0.53 cm h$^{-1}$ from 13 to 21 WAT, respectively).
Figure 2.8: Field saturated hydraulic conductivity ($K_{fs}$) as affected by different tillage and irrigation management practices at three depths in wheat. WAT = weeks after tillage.

2.5 Conclusions and the need for future research

Tillage implements change soil physical and hydraulic properties depending on their type and depth of influence. Moldboard plow decreases $\rho_b$ and increases $\varphi$ up to 20 cm depth. This increase in $\varphi$ is mainly due to the increase in $\varphi_{>10}$, which cannot retain water under the action of gravity. This conclusion was supported by the observed higher $\theta_v$ immediately after rain or irrigation events and higher $K_{fs}$ in moldboard plow. Flood irrigation increased $\theta_v$, in all tillage treatments, more than the sprinkler irrigation but soil drained quicker in moldboard plow due to greater $\varphi_{>10}$. Moldboard plow had lower $\theta_{PAWC}$ than the chisel plow and cultivator but still higher grain and straw yields. The increase in yield was attributed to better root growth and resulting greater water uptake. Water retention at matric pressures slightly higher than $\psi_{FC}$ (~10 kPa) may help to quantify the pores somewhat larger than 10 μm (but smaller than 30 μm), which
transmit water very slowly and may still be useful for plant uptake. Higher $\theta_v$ in sprinkler irrigation than flood irrigation at the end of wheat crop season and greater decrease in $K_{fs}$ over time with flood irrigation than sprinkler irrigation, especially in moldboard plow, provided evidence of the fact that soil reconsolidation after tillage is greater with flood irrigation than sprinkler irrigation and moldboard plow is more prone to it. The CS616 responded effectively to changes in $\theta_v$ and was able to provide the comparison between different tillage and irrigation treatments but exhibited more diurnal variations at higher temperatures creating doubts about the absolute values of $\theta_v$. More useful information can be generated by increasing the soil core sampling times and including variably saturated hydraulic properties in the determinations to gain better insight as to how hydraulic properties change with time. Other management practices like green manuring and crop residue management, which also modify the soil physical and hydraulic properties, should also be tested for their temporal effects on $\theta_v$ and soil hydraulic properties.

2.6 References


Christiansen, J.E. 1942. Irrigation by sprinkling. Agricultural Experiment Station, Bulletin 670. University of California, Berkley, CA, USA.


Chapter 3

Temporal variability of soil physical and hydraulic properties under different tillage and irrigation management in maize

3.1 Abstract

An experiment was conducted on maize to investigate the effect of three tillage practices (Cultivator, Moldboard plow and Chisel plow) and two irrigation techniques (Flood and Sprinkler) on soil physical properties and temporal variations in soil hydraulic properties. Moldboard plow resulted in significantly higher grain and stover yield followed by chisel plow and cultivator, while irrigation techniques did not have a significant effect on yield. The soil volumetric water content ($\theta_v$) dynamics, monitored hourly after a heavy spell of monsoon rains following tillage, showed a greater increase in $\theta_v$ with moldboard plow in response to irrigations and a quicker drying than the other two tillage types. The highest soil bulk density ($\rho_b$) and the lowest soil total porosity ($\phi$), as determined from the core samples taken at the end of the growing season, were observed with cultivator under flood irrigation, whereas the lowest $\rho_b$ and the highest $\phi$ were measured where moldboard plow was sprinkler irrigated. Similarly, cultivator after flood irrigation had the highest $\theta_v$, while moldboard plow after sprinkler irrigation had the lowest $\theta_v$ at high matric pressures (−30 and −100 kPa). Cultivator and chisel plow had significantly higher plant available water capacity ($\theta_{PAWC}$) than moldboard plow. The effect of tillage types was mainly on water transmission pores (> 10 μm) where
moldboard plow had the highest volume of transmission pores followed by chisel plow and cultivator. Sprinkler irrigated plots had higher volume of transmission pores than flood irrigated plots at 10 cm depth. Field saturated hydraulic conductivity \( (K_{fs}) \) determined before irrigation and at the end of crop season decreased significantly. Flood irrigation was responsible for causing a greater decrease in \( K_{fs} \) with highest magnitude of change in moldboard plow. Even after several rains just after tillage operations, \( K_{fs} \) decreased significantly with flood irrigation. The results highlight that tillage systems change soil physical and hydraulic properties depending on their type and depth. Irrigation techniques have significantly different effects on soil reconsolidation even after excessive rains. Soil hydraulic properties may be optimized with the combination of suitable tillage and irrigation for efficient utilization of water resources.

3.2 Introduction

In spite of a large number of field studies conducted to evaluate tillage effects on the hydraulic functioning of structured soils, the information available in the literature about short-term tillage-induced effects on the hydrophysical properties of agricultural soils and their dynamics is very scarce (Green et al., 2003). The studies on this subject have shown inconsistent results regarding soil physical and hydraulic properties under different tillage systems due to the transitory nature of soil structure after tillage, site history, initial and final water content, the time of sampling and the extent of soil disturbances (Azooz and Arshad, 1996). Generally, under tillage systems that include...
plowing, soil hydraulic conductivity increases upon tillage events and then decreases during the growing season due to the settling of the soil structure created by tillage (Angulo-Jaramillo et al., 1997; Azevedo et al., 1998; Bormann and Klaassen, 2008). The structural changes in recently tilled soils are caused by precipitation or irrigation (Green et al., 2003) and associated wetting and drying cycles thus leading to a decrease in hydraulic conductivity (Cameira et al., 2003; Petersen et al., 2008; Schwartz et al., 2003), which can be attributed to a reduction in the fraction of conductive mesopores (Messing and Jarvis, 1993) in conjunction with a concomitant increase in bulk density (Mellis et al., 1996).

Crop type can also affect soil water distributions and soil hydraulic properties either directly by root water uptake (Feddes et al., 1988; Zhuang et al., 2001) or indirectly by modifying the soil pore structure through the growing root system (Angers and Caron, 1998; Kodešová et al., 2006; Rasse et al., 2000). The crop plants varying in root systems and water requirements may affect soil physical and hydraulic properties differently. Cereal crops develop either concentrated or scattered type of root system depending on the angle of growth of lateral roots. Maize has a scattered type of root system with fewer but longer nodal roots, many of which run obliquely and vertically in the soil profile (Grzesiak, 2009). This experiment was conducted with an objective to determine the effect of tillage practices and irrigation techniques on temporal variability of soil water content and physico-hydraulic properties during maize production season.
3.3 Materials and Methods

This experiment was conducted during 2010 to investigate the effect of different tillage and irrigation techniques on soil physical and hydraulic properties in maize on the same experimental area of National Agricultural Research Centre (NARC), Islamabad, Pakistan where the experiment on wheat (Chapter 2) was conducted. Details about the soil classification and physical properties along with the climate of the area have been mentioned earlier (Section 2.3).

3.3.1 Experimental Layout and Treatments

The experiment was laid out in a strip plot design with four replications. The layout plan (Figure 2.2) of the previous wheat crop was reproduced for the subsequent maize crop. Three tillage methods (Cultivator, moldboard plow and chisel plow) and two irrigation techniques (Flood and sprinkler irrigation) were repeated on the same layout. The sequence of tillage operations was the same as detailed for wheat crop (Section 2.3.1). The pre-sowing irrigation was not applied to the experimental field because of sufficient moisture already present in the soil due to the rains before planting. Tillage operations and fertilizer application were done in the third week of July 2010. Half of the recommended dose of N (75 kg ha\(^{-1}\)) as urea and full recommended doses of P\(_2\)O\(_5\) (90 kg ha\(^{-1}\)) as triple superphosphate and K\(_2\)O (50 kg ha\(^{-1}\)) as sulphate of potash were applied as a basal dose of fertilizers. Unfortunately, sowing could not be done the same day. A heavy spell of monsoon rains started (Figure 3.1), resulting in maize sowing delayed for a month. A short duration, late variety of maize (Zea mays L. variety: Swan-
3) was selected to cope with the circumstances. It was not advisable to repeat the tillage operations due to higher than optimum moisture and still more rains were expected. The crop was planted with a maize planter with a row to row distance of 75 cm and plant to plant distance of 20 cm in the third week of August 2010. The second half of nitrogen fertilizer was applied two months after sowing just before a rain event. Irrigation water channels and plot boundaries were constructed again according to the wheat layout plan (Figure 2.2). The crop was harvested in the first week of December 2010.

Irrigation methods have been discussed in Section 2.3.2. Flood irrigation (7.5 cm depth of water) as basin irrigation using gravity flow and sprinkler irrigation (5 cm depth of water) with a moving rain-gun sprinkler were applied to the respective plots (Figure 2.2) in the second and third weeks of November 2010 respectively, when the crop was at the critical blister stage. The flood irrigation was controlled with a cut-throat flume fixed in the main water channel. The rotary sprinkler irrigation was applied to the rectangular field in two stages rotating the rain-gun sprinkler in a sector of the circle. The average wind speed on the day of sprinkler irrigation was 0.88 km h\(^{-1}\). The reason behind only one irrigation event was the frequent and high amount of rainfall during and before the growing season. The average seasonal irrigation demand of maize is 300-400 mm (Tariq et al., 2003); while it received 268 mm of rain during the growing season, it had also received 534 mm of rain in the month before sowing after tillage (Figure 9). The total pan evaporation after tillage and during the growing season was 453 mm recorded at a meteorological station near the experimental field.
3.3.2 Monitoring Soil Water Content and Soil Temperature

Soil volumetric water content, $\theta_v$ (m$^3$ m$^{-3}$), was monitored similarly as for the wheat crop (Section 2.3.3) using CS616 WCR. The WCRs were installed horizontally at 10 and 20 cm depths in every treatment combination in two of the four replication blocks with an endeavor to re-open the same pits, as for the wheat crop, in the last week of October 2010. The output period was logged hourly and $\theta_v$ was calculated using the same calibration equation. Soil temperature (°C) was also monitored with type-T (Copper-Constantan) thermocouples installed at the same depths, 20 cm away from WCRs.

Figure 3.1: Daily rainfall and maximum and minimum air temperatures recorded during the maize growing season at a meteorological station located 1 km (aerial distance) from the experimental field.
3.3.3 Monitoring Soil Water Potential

Total pore water potential was measured by tensiometers pre-hydrated and installed in the first week of November 2010, as close to as practical and at the same depths as WCRs and thermocouples. Soil water suction was recorded by digital Tensimeter twice a week as described in Section 2.3.4.

3.3.4 Determination of Field Saturated Hydraulic Conductivity

The Guelph Pressure Infiltrometer (GPI) attachment to the Guelph Permeameter (GP) reservoir (Soil Moisture Equipment Corp., Santa Barbara, CA, USA) was used to measure steady state infiltration rate \( L^3 T^{-1} \) at three sites from all treatment combinations in two replications. The measurements were carried out at a single ponding depth of 10 cm in 1st week of November 2010 and 2nd week of December 2010, i.e., 17 weeks and 23 weeks after tillage operations, respectively, according to the method described in Section 2.3.4. The \( K_{fs} \) was calculated from the quasi-steady flow rate out of the cylinder (W. D. Reynolds, 2008a) taking the value of macroscopic capillary length parameter \( \alpha^* \) as 0.12 cm\(^{-1}\), which is appropriate for agricultural soils (W. D. Reynolds, 2008b).

3.3.5 Determination of Soil Water Retention Characteristics and Bulk Density

Intact soil cores were collected from 10, 20 and 30 cm depths from all treatment plots in two replications in the 1\(^{st}\) week of December 2010 after harvesting the maize crop (Method described in Section 2.3.5). The core samples were wrapped in polythene paper and brought to the laboratory. Water retention was determined at \(-30\ (\psi_{FC})\),
−100 (ψ_{100}), −500 (ψ_{500}), −1000 (ψ_{1000}) and −1500 (ψ_{PWP}) kPa of matric pressures, ψ_m, using pressure-plate extractors (Soilmoisture Equipment Corp., Santa Barbara, CA, USA), where ψ_{FC} and ψ_{PWP} are the matric pressures at field capacity and permanent wilting point, respectively. Water content was determined gravimetrically and converted to volumetric water content, \( \theta_v (m^3 m^{-3}) \) at each \( \psi_m \) (W.D. Reynolds and Topp, 2008). The soil core samples, after determining \( \theta_v \) at all \( \psi_m \), were oven dried at 105°C to determine the soil bulk density, \( \rho_b (Mg m^{-3}) \) and to calculate total porosity, \( \varphi \). Plant available water capacity (\( \theta_{PAWC} \)) was calculated as the difference in \( \theta_v \) retained between \( \psi_{FC} \) and \( \psi_{PWP} \), i.e., \( \theta_{FC} \) and \( \theta_{PWP} \), respectively (Romano and Santini, 2002). Volume of soil occupied by pores of various diameter classes (<0.2 μm (\( \varphi_{<0.2} \)), 0.2-0.3 μm (\( \varphi_{0.2-0.3} \)), 0.3-0.6 μm (\( \varphi_{0.3-0.6} \)), 0.6-3 μm (\( \varphi_{0.6-3} \)), 3-10 μm (\( \varphi_{3-10} \)) and >10 μm (\( \varphi_{>10} \)) was computed from the soil water retention data assuming soil pores to be cylindrical and contact angle of water to the capillary pores as zero (Flint and Flint, 2002).

### 3.3.6 Statistical Analysis

#### 3.3.6.1 Temporal Stability of Soil Water Content

Soil water content data were subject to temporal stability analysis using the approach of Vachaud et al. (1985) extended further to include measurements made at different depths (Hu et al., 2010). The concept was used to evaluate temporal persistence of the relative differences in soil water content and their stability as affected by different soil management practices applied in the experimental field. The analysis was conducted for two time periods, i.e., before and after irrigation events.
numbers of hourly observations recorded for flood and sprinkler irrigations were not equal because they were applied at different days resulting in separate analysis for both the irrigation techniques. Replication-averaged measurements for three tillage treatments (taken as plots) and two depths were evaluated. Calculations regarding time averaged relative difference ($\tilde{\delta}_{ij}$) of soil water content and its standard deviation ($\sigma(\tilde{\delta}_{ij})$) have been discussed earlier (Section 2.3.7.1).

3.3.6.2 Analysis of Variance

Variance analyses were performed with SAS software version 9.1 (SAS Institute Inc., Cary, NC, USA) using Proc Mixed model. The data parameters determined were handled differently depending on their structure. Block, tillage and irrigation were taken as classification variables for all parameters and depth, time, pressure heads and pore classes as non-randomized repeated measures for the respective parameters. Further details about the analysis are described in Section 2.3.7.2.

3.4 Results and Discussion

3.4.1 Grain and Stover Yield

Although tillage practices significantly affected grain ($P = 0.0010$) and stover ($P = 0.0005$) yield (Table 3.1), the effect of irrigation techniques was not significant. The moldboard plow treatment resulted in the highest grain ($6113 \text{ kg ha}^{-1}$) and stover ($5046 \text{ kg ha}^{-1}$) yield. Chisel plow and cultivator were similar to each other in terms of both the yield parameters but significantly lower than the moldboard plow. Moldboard plow had
21 and 23% higher grain and stover yield, respectively, whereas chisel plow had only 3 and 4% higher grain and stover yield than the cultivator, respectively.

Table 3.1: Yield parameters (kg ha\(^{-1}\)) of maize as affected by tillage and irrigation practices.

<table>
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<th>Chisel</th>
<th>Mean</th>
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**Stover Yield**

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<th>Chisel</th>
<th>Mean</th>
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<td>4412</td>
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<tr>
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<td>4092 B</td>
<td>5046 (23) A</td>
<td>4260 (4) B</td>
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</tr>
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</table>

Means sharing same letters are not statistically different at \(\alpha = 0.05\). Values in the parenthesis are percent increase over cultivator.

The interaction between tillage and irrigation was not significant but the effect of sprinkler irrigation on grain yield was numerically greater with moldboard plow while its effect on stover yield was greater with chisel plow. Improved yield parameters in moldboard plow may be attributed to the lower bulk density and higher total porosity (Table 3.2) with moldboard plow and the resulting greater root growth and water uptake (Chaudhary et al., 1985).
3.4.2 Soil Water Content

The dynamics of volumetric water content ($\theta_v$) in soil monitored hourly throughout the maize growth period at two depths for various tillage and irrigation treatments are presented in Figure 3.2. Since the monitoring started after the spell of monsoon rains followed by a dry spell, no variation in $\theta_v$ in response to rainfall was observed with time. There was only one rain event of 4 mm in the mid of November, 2010 which did not change $\theta_v$. However, the flood and sprinkler irrigations were clearly detected by an increase in $\theta_v$ in second and third week of November, respectively.

![Figure 3.2: Temporal changes in volumetric water content ($\theta_v$) of soil as affected by different tillage and irrigation management practices at two depths in maize.](image-url)
The $\theta_v$ was high in the beginning of the observation period and decreased gradually during drying periods for all the tillage treatments before and after respective irrigations. The increase in $\theta_v$ after irrigation and decrease on drying was sharper at 10 cm depth. Higher $\theta_v$ was generally observed away from irrigation events at 20 cm depth for all combinations of tillage and irrigation. Diurnal variations were higher at 10 cm than at 20 cm depth possibly due to more temperature fluctuation near the surface (Evett et al., 2011).

The flood and sprinkler irrigations resulted in an abrupt rise in $\theta_v$. A depth-wise comparison showed that this increase was greater at 10 cm than at 20 cm depth for both irrigations and an irrigation-wise comparison revealed that the flood irrigation caused a higher rise in $\theta_v$ than the sprinkler irrigation for both depths. During the initial monitoring period before irrigation, the $\theta_v$ for different tillage treatments were not very different at 10 cm depth with a similar pattern of drying. However, moldboard plow and chisel plow had higher $\theta_v$ at 20 cm depth for flood irrigation plots, whereas chisel plow was lowest for sprinkler irrigation.

Flood irrigation caused $\theta_v$ to increase the greatest in case of moldboard plow followed by chisel plow and cultivator. This difference in $\theta_v$ between tillage treatments proved to be temporary at 10 cm depth as $\theta_v$ decreased for all tillage treatments to become approximately equal in water content within a day. Afterwards, the $\theta_v$ at this depth for all tillage practices were similar during the drying period. This may be related to the fact that complete reconsolidation of the soil to its original state occurred after the final flooding. The changes in $\theta_v$ after flood irrigation were more stable at 20 cm
depth with moldboard plow showing greater water content just after irrigation followed by chisel plow and cultivator. During the drying period after irrigation, the $\theta_v$ in moldboard and chisel plow remained similar but higher than the cultivator at this depth. Similar $\theta_v$ for moldboard and chisel plow likely corresponds to their similar depth of cultivation, with cultivator having the shallowest depth of cultivation. The reconsolidation of soil was slower at 20 cm depth and was completed by the end of the crop growth period.

Sprinkler irrigation resulted in higher $\theta_v$ in moldboard plow and cultivator than chisel plow at both depths but moldboard plow dried quicker than the cultivator at 10 cm depth. This may be attributed to the lower bulk density and higher total porosity in moldboard plow (Table 3.2) and the resulting improvement in root growth and water uptake in this case. Moldboard plow and cultivator were both drying quicker than the chisel plow at 20 cm depth. However, surprisingly, the $\theta_v$ after sprinkler irrigation in chisel plow did not rise as much as in moldboard plow and cultivator especially at 20 cm depth. The water content in chisel plow remained lowest throughout the monitoring period.

Time averaged relative difference ($\bar{\delta}_{ij}$) and standard deviation ($\sigma(\bar{\delta}_{ij})$) of $\theta_v$ for different tillage practices and irrigation techniques at two depths before and after irrigation events are plotted in Figure 3.3. Temporal stability of the $\theta_v$ decreased with the flood irrigation and the effect was more pronounced at 20 cm depth. This effect could not be identified with the sprinkler irrigation. The patterns of time averaged relative difference regarding different tillage practices did not change at both depths.
before and after flood or sprinkler irrigation (Figure 3.3). The temporal variability in $\theta_v$ decreased with the flood irrigation but not with the sprinkler irrigation. Hence, only the flood irrigation reverted back the effects of different tillage practices close to field average in terms of measured $\theta_v$.

Figure 3.3: Time averaged relative difference ($\bar{\delta}_{ij}$) of soil water content as affected by different tillage and irrigation management practices at two depths in maize. Error bars represent the standard deviation ($\sigma(\bar{\delta}_{ij})$).

3.4.3 Soil Temperature

Fluctuation in soil temperature (Figure 3.4) under different tillage practices and irrigation techniques at two depths indicated a decreasing trend during the maize
growing season in all cases. Tillage practices and irrigation techniques did not affect the soil temperature but the declining atmospheric temperature (Figure 3.1) was likely responsible for the decreasing trend. Daily maximums were higher and the minimums were lower closer to the surface (10 cm) than at 20 cm depth. The observations recorded in the first half of the monitoring period were quite regular but unfortunately the second half of the growing season to be more erratic showing frequent irregular increases and decreases in soil temperature.

Spatial patterns of the temporal stability of soil temperature (Appendix II) showed that the cultivator and moldboard plow became less stable at 20 cm depth after
the flood irrigation while they became more stable after sprinkler irrigation at 10 cm depth, other treatments being generally very stable with time. Cultivator had the highest and moldboard plow had the lowest, but not significant, time averaged relative differences in soil temperature at both depths before and after flood irrigation, whereas the reverse was true before and after sprinkler irrigation only at 20 cm depth. At 10 cm depth, chisel plow had higher time averaged relative difference than the cultivator and moldboard plow before sprinkler irrigation, while cultivator had higher time averaged relative difference than the moldboard and chisel plow after sprinkler irrigation.

3.4.4 Soil Bulk Density and Total Porosity

Effects of tillage and irrigation on soil bulk density ($\rho_b$) and the resulting total porosity ($\varphi$) at three soil depths (Table 3.2) depict that the $\rho_b$ increased causing the $\varphi$ to decrease significantly ($P = 0.0408$) with depth. The main effects of tillage and irrigation along with all interactions were not significant at $\alpha = 0.05$. The highest $\rho_b$ (1.62 and 1.65 Mg m$^{-3}$, respectively) and the lowest $\varphi$ at 10 and 20 cm depths was observed where cultivator was flood irrigated, whereas the lowest $\rho_b$ (1.50 and 1.54 Mg m$^{-3}$, respectively) and the highest $\varphi$ at these depths was measured where moldboard plow was sprinkler irrigated. The difference between the $\rho_b$ at 10 and 20 cm depths was lower in case of moldboard and chisel plow but higher in cultivator. Sprinkler irrigation after all the tillage treatments had lower $\rho_b$ and higher $\varphi$ than those of the flood irrigation especially at 10 cm depth.
Table 3.2: Bulk density ($\rho_b$), total porosity ($\varphi$) and plant available water capacity ($\theta_{PAWC}$) as affected by tillage and irrigation practices at three depths in maize.

<table>
<thead>
<tr>
<th>Tillage</th>
<th>Irrigation</th>
<th>$\rho_b$ (Mg m$^{-3}$)</th>
<th>$\varphi$</th>
<th>$\theta_{PAWC}$ (m$^3$ m$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>10 cm</td>
<td>20 cm</td>
<td>30 cm</td>
</tr>
<tr>
<td>Cultivator</td>
<td>Flood</td>
<td>1.62</td>
<td>1.65</td>
<td>1.65</td>
</tr>
<tr>
<td></td>
<td>Sprinkler</td>
<td>1.57</td>
<td>1.64</td>
<td>1.65</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>1.59</td>
<td>1.65</td>
<td>1.65</td>
</tr>
<tr>
<td>Moldboard</td>
<td>Flood</td>
<td>1.54</td>
<td>1.56</td>
<td>1.66</td>
</tr>
<tr>
<td></td>
<td>Sprinkler</td>
<td>1.50</td>
<td>1.54</td>
<td>1.63</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>1.52</td>
<td>1.55</td>
<td>1.65</td>
</tr>
<tr>
<td>Chisel</td>
<td>Flood</td>
<td>1.61</td>
<td>1.61</td>
<td>1.64</td>
</tr>
<tr>
<td></td>
<td>Sprinkler</td>
<td>1.55</td>
<td>1.60</td>
<td>1.64</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>1.58</td>
<td>1.60</td>
<td>1.64</td>
</tr>
</tbody>
</table>
Similar $\rho_b$ and $\varphi$ for all the tillage practices and irrigation techniques may be related to the natural reconsolidation during cycles of wetting and drying after tillage (Green et al., 2003). Since the core sampling for water retention characteristics and $\rho_b$ was done after harvesting the maize crop and there was a long spell of heavy monsoon rains after tillage with a couple of events with more than 100 mm of rain and a couple with more than 50 mm of rain, the resulting reconsolidation (towards original) of the soil loosened by different tillage practices may be related to these factors.

### 3.4.5 Soil Water Retention

Soil water retention ($\theta_v(\psi_m)$) characteristic curves (Figure 3.5) for different combinations of tillage and irrigation at three depths depict that the main effects of tillage and irrigation were statistically not significant at $\alpha = 0.05$, but those of soil depth ($P = 0.0375$) and matric pressure ($\psi_m$, $P < 0.0001$) were significant. The water retained at 10 cm depth was not significantly lower than that at 20 cm depth but it was significantly lower than at 30 cm depth. The $\theta_v$ at various $\psi_m$ averaged over tillage, irrigation and depth significantly decreased with increasing $\psi_m$. The interactive effects between tillage $\times$ depth ($P < 0.0001$), tillage $\times$ pressure ($P = 0.0206$) and depth $\times$ pressure ($P = 0.0108$) on $\theta_v$ were also significant.

The differences in $\theta_v(\psi_m)$ for various tillage and irrigation treatments at the depths studied were not significant ($\alpha = 0.05$). However, noticeable differences were observed at 10 and 20 cm depths especially at higher $\psi_m$ ($\psi_{FC}$ and $\psi_{100}$), whereas at lower $\psi_m$ ($\psi_{500}$, $\psi_{1000}$ and $\psi_{PWP}$) the $\theta_v$ was similar for all tillage practices and
irrigation techniques. At 30 cm depth, $\theta_v(\psi_m)$ was mostly higher than the shallower depths and there was no response of tillage or irrigation treatments.

Figure 3.5: Soil water retention characteristics ($\theta_v(\psi_m)$) as affected by different tillage and irrigation management practices at three depths in maize.

Cultivator after flood irrigation had the highest $\theta_v$, whereas moldboard plow after sprinkler irrigation had the lowest $\theta_v$ for all $\psi_m$ at 10 and 20 cm depths, but the order of other combinations of tillage and irrigation was different for both the depths.

The order of $\theta_v(\psi_m)$ at 10 cm depth was cultivator flood irrigated > chisel plow flood irrigated > cultivator sprinkler irrigated > chisel plow sprinkler irrigated > moldboard plow flooded irrigated > moldboard plow sprinkler irrigated and at 20 cm depth it was cultivator flood irrigated > cultivator sprinkler irrigated > chisel plow flood irrigated >
chisel plow sprinkler irrigated > moldboard plow flood irrigated > moldboard plow sprinkler irrigated.

Although the effect of tillage × irrigation × depth × matric pressure interaction was not significant (\(\alpha = 0.05\)) due to higher order interaction, the data have been plotted (Figure 3.5) along with the error bars representing standard error of replication means for the sake of explanation. The most prominent differences in \(\theta_v\) retained were observed at \(\psi_{FC}\) (i.e. \(\theta_{FC}\)) at 10 and 20 cm depths. In flood irrigated plots, the \(\theta_{FC}\) was lower in moldboard plow than cultivator and chisel plow which had similar \(\theta_{FC}\) at 10 cm depth. The trend of \(\theta_v\) at \(\psi_{100}\) and \(\psi_{500}\) was similar for tillage treatments but with lower differences amongst them at this depth than at 20 cm. The similarity of \(\theta_v\) in the case of cultivator and chisel plow at this depth may be attributed to their resemblance in the type of soil manipulation resulting in similar pore geometry. The inversion and pulverization of the soil with moldboard plow may be responsible for larger soil pores than those retaining water at \(\psi_{FC}\) (transmission pores) and the consequent lower \(\theta_v\) at higher \(\psi_{im}\) studied. Evidence to support this statement is that moldboard plow had the highest volume of water transmission pores (> 10 μm in diameter, Table 3.3) as well as field saturated hydraulic conductivity (Figure 3.7). The tillage treatments receiving sprinkler irrigation showed lower \(\theta_{FC}\) than the respective treatments receiving flood irrigation at 10 cm depth. The trend of \(\theta_v\) at \(\psi_{FC}\), \(\psi_{100}\) and \(\psi_{500}\) within sprinkler irrigated tillage treatments was the same as for flood irrigated treatments at 10 cm depth; so the pattern depended more on the type of tillage than the kind of irrigation.
The situation was different at 20 cm depth where the highest $\theta_{FC}$ was observed with cultivator when flood irrigated closely followed by that after sprinkler irrigation. Moldboard plow exhibited the lowest values at this depth keeping a similar pattern for the two kinds of irrigation. Chisel plow displayed an intermediate behavior at this depth showing the $\theta_{FC}$ higher and close to that of cultivator when it was flood irrigated while lower and close to moldboard plow when sprinkler irrigated. At $\psi_{100}$ and $\psi_{500}$ the tendency of $\theta_v$ was the same as $\theta_{FC}$ for all combinations of tillage and irrigation. This observation shows that there was a change of soil behavior in the case of chisel plow at 20 cm depth, which showed lower $\theta_v$ than the cultivator both with flood and sprinkler irrigation especially at higher $\psi_m$. This may be associated with the fact that the chisel plow being a deeper tillage instrument than the cultivator, has affected the $\theta_v(\psi_m)$ at 20 cm depth, somewhat like the moldboard plow.

The relationship between $\theta_v$ (from WCRs) and $\psi_m$ (from tensiometers) as observed twice a week in the field throughout the growing season is presented in Figure 3.6. The $\psi_m$ remained from $-65$ to $-25$ kPa most of the time showing that soil matric potential persisted at the higher end of plant available water range during the season. The $\theta_v$ was lower at 10 cm depth than at 20 cm depth in moldboard plow for both types of irrigation. This might be due to higher $\varphi_{>10}$ at 10 cm depth (Table 3.3) draining easily into 20 cm depth with lower $\varphi_{>10}$. The relationship is more typical in flood irrigated plots for all tillage types. This might be due to a single drying cycle except a couple of observations before irrigation events.
Figure 3.6: The relationship between volumetric water content ($\theta_v$) and soil matric potential ($\psi_m$) as affected by different tillage and irrigation management practices at two depths in maize. Brown and blue points show measurements taken before and after irrigations, respectively.
3.4.6 Plant Available Water Capacity

Plant available water capacity ($\theta_{PAWC}$) is displayed in Table 3.2. Although the main effects of tillage and irrigation were not significant ($\alpha = 0.05$), the cultivator treatment had higher $\theta_{PAWC}$ than the moldboard plow. The chisel plow had $\theta_{PAWC}$ in between them but closer to the cultivator. All the tillage treatments had higher $\theta_{PAWC}$ at 10 cm depth than that at 20 cm depth. The highest $\theta_{PAWC}$ (0.18 m$^3$ m$^{-3}$) was observed in the case of cultivator when flood irrigated at 10 cm depth and the lowest (0.13 m$^3$ m$^{-3}$) where sprinkler irrigation was applied after moldboard plowing.

3.4.7 Pore Size Distribution

The volume of pores in the pore diameter classes (Table 3.3) showed significant differences ($P < 0.0001$). On average, the pores < 0.2 μm in diameter (pores containing unavailable water) acquired most of the volume followed by the pores > 10 μm diameter (freely draining pores), both of them comprising almost 60 % of the total pores leaving about 40 % for the pores capable of holding water for plant uptake. The interactive effect of tillage × pore class elucidated that tillage types significantly ($P < 0.0001$) affected the volume of pores > 10 μm in diameter where the moldboard plow had the highest volume (0.09 m$^3$ m$^{-3}$) followed by chisel plow (0.06 m$^3$ m$^{-3}$) and cultivator (0.03 m$^3$ m$^{-3}$). The effect of depth × pore class interaction explicated that the volume of pores > 10 μm in diameter at 10 and 20 cm depth was significantly ($P < 0.0001$) higher, while that belonging to pore class 0.6-3 μm in diameter was significantly lower than those at 30 cm depth.
Table 3.3: Volume of pores (m$^3$ m$^{-3}$) of various size classes as affected by tillage and irrigation practices in three soil depths in maize.

<table>
<thead>
<tr>
<th>Tillage</th>
<th>Irrigation</th>
<th>Pore Diameter ($\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>&lt; 0.2</td>
</tr>
<tr>
<td><strong>10 cm</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cultivator Flood</td>
<td>0.187</td>
<td>0.026</td>
</tr>
<tr>
<td>Sprinkler</td>
<td>0.174</td>
<td>0.018</td>
</tr>
<tr>
<td>Mean</td>
<td>0.180 a</td>
<td>0.022 n-q</td>
</tr>
<tr>
<td>Moldboard Flood</td>
<td>0.168</td>
<td>0.020</td>
</tr>
<tr>
<td>Sprinkler</td>
<td>0.163</td>
<td>0.019</td>
</tr>
<tr>
<td>Mean</td>
<td>0.166 a</td>
<td>0.019 o-p</td>
</tr>
<tr>
<td>Chisel Flood</td>
<td>0.179</td>
<td>0.025</td>
</tr>
<tr>
<td>Sprinkler</td>
<td>0.169</td>
<td>0.017</td>
</tr>
<tr>
<td>Mean</td>
<td>0.174 a</td>
<td>0.021 n-q</td>
</tr>
<tr>
<td><strong>20 cm</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cultivator Flood</td>
<td>0.194</td>
<td>0.020</td>
</tr>
<tr>
<td>Sprinkler</td>
<td>0.186</td>
<td>0.016</td>
</tr>
<tr>
<td>Mean</td>
<td>0.190 a</td>
<td>0.018 o-q</td>
</tr>
<tr>
<td>Moldboard Flood</td>
<td>0.165</td>
<td>0.016</td>
</tr>
<tr>
<td>Sprinkler</td>
<td>0.163</td>
<td>0.018</td>
</tr>
<tr>
<td>Mean</td>
<td>0.164 a</td>
<td>0.017 pq</td>
</tr>
<tr>
<td>Chisel Flood</td>
<td>0.177</td>
<td>0.019</td>
</tr>
<tr>
<td>Sprinkler</td>
<td>0.174</td>
<td>0.022</td>
</tr>
<tr>
<td>Mean</td>
<td>0.175 a</td>
<td>0.021 n-q</td>
</tr>
<tr>
<td><strong>30 cm</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cultivator Flood</td>
<td>0.191</td>
<td>0.019</td>
</tr>
<tr>
<td>Sprinkler</td>
<td>0.181</td>
<td>0.018</td>
</tr>
<tr>
<td>Mean</td>
<td>0.186 a</td>
<td>0.019 o-q</td>
</tr>
<tr>
<td>Moldboard Flood</td>
<td>0.194</td>
<td>0.022</td>
</tr>
<tr>
<td>Sprinkler</td>
<td>0.180</td>
<td>0.008</td>
</tr>
<tr>
<td>Mean</td>
<td>0.187 a</td>
<td>0.015 q</td>
</tr>
<tr>
<td>Chisel Flood</td>
<td>0.194</td>
<td>0.012</td>
</tr>
<tr>
<td>Sprinkler</td>
<td>0.188</td>
<td>0.018</td>
</tr>
<tr>
<td>Mean</td>
<td>0.191 a</td>
<td>0.015 q</td>
</tr>
</tbody>
</table>

Means sharing same letters are statistically not different at $\alpha=0.05$.  

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The effect of three way interaction between tillage × depth × pore class (P < 0.0001) further resulted in the moldboard plow treatment having significantly higher volume of pores > 10 μm in diameter than chisel plow and cultivator at 10 (0.12 m³ m⁻³) and 20 cm (0.12 m³ m⁻³) depths. Although the volume of pores of this class in the case of chisel plow (0.07 and 0.07 m³ m⁻³, respectively) was lower than the moldboard plow, it was significantly higher than those of the cultivator (0.05 and 0.03 m³ m⁻³, respectively) at these depths. The effect of cultivator on the volume of pores of this class was only observed at 10 cm depth.

The volume of pores < 0.2 μm was not affected by different combinations of tillage and irrigation at all depths but it was significantly higher than that of the other pore classes. It was obvious that the effect of tillage types was mainly on the water transmission pores (> 10 μm in diameter) and the effect of moldboard and chisel plow extended down to 20 cm depth with moldboard plow being more effective in this case. The irrigation × depth × pore class (P = 0.0014) interaction revealed that sprinkler irrigation had significantly higher volume (0.10 m³ m⁻³) of pores > 10 μm in diameter than that of flood irrigation (0.06 m³ m⁻³) at 10 cm depth. Thus the flood irrigation was responsible for reducing the volume of pores which can transmit water easiest beneath the surface soil.

3.4.8 Field Saturated Hydraulic Conductivity

The effect of tillage types on field saturated hydraulic conductivity (\(K_{fs}\)) was significant (P = 0.0141). Moldboard plow exhibited significantly higher \(K_{fs}\) (0.90 cm h⁻¹)
than the chisel plow (0.64 cm h\(^{-1}\)) and cultivator (0.53 cm h\(^{-1}\)). Though the \(K_{fs}\) decreased with time from 13 WAT to 21 WAT by 23 %, the difference was not significant. The effect of irrigation techniques and all possible interactions between tillage, irrigation and WAT were not significant, but it was observed that the moldboard plow after 17 weeks had 42 % higher \(K_{fs}\) with sprinkler irrigation (1.02 cm h\(^{-1}\)) than after 23 weeks with flood irrigation (0.72 cm h\(^{-1}\)). It becomes evident that even after receiving 802 mm of rain before the first determination of \(K_{fs}\), it decreased markedly within 6 weeks with negligible rain and only one event of irrigation and flood irrigation was responsible for reducing it more than the sprinkler irrigation (Figure 3.7).

![Figure 3.7: Field saturated hydraulic conductivity \((K_{fs})\) as affected by different tillage and irrigation management practices at three depths in maize.](image)

### 3.5 Conclusions and the need for future research

A heavy spell of monsoon rains (806 mm) following tillage operations was the primary factor affecting soil physical and hydraulic properties in this experiment. The rains caused most of the soil reconsolidation, generally increasing \(\rho_b\) and decreasing \(\varphi\).
The $\rho_b$ was lowest in moldboard plow corresponding to a higher $\varphi$ up to 20 cm depth at the end of the experiment but the differences between tillage treatments were not significant. However, $\varphi_{>10}$ was significantly higher in moldboard plow resulting in higher $K_{fs}$ at the soil surface. Flood irrigation caused a greater increase in $\theta_v$ than sprinkler irrigation in all tillage treatments but it drained quicker in moldboard plow. The tillage types had similar $\theta_{PAWC}$ yet moldboard plow had higher grain and stover yields, attributed to better root growth and resulting water uptake. Despite the huge rains after tillage, the decrease in $K_{fs}$ due to flood irrigation was greater than with sprinkler irrigation and the reduction was greatest in moldboard plow. It can be concluded that soil reconsolidation after tillage continued even after the large downpours and the combination of moldboard plow and sprinkler irrigation exhibited the least soil settlement. Although CS616 was able to monitor the changes in $\theta_v$, it exhibited high diurnal variations creating doubts about the absolute values of $\theta_v$. It can effectively be used for comparative studies in the field. In future, if core samples are collected at various times during the crop season, the patterns of temporal changes in soil physical and hydraulic properties after tillage can be monitored more effectively. Additionally, variably saturated hydraulic properties measured at different times may give useful information. Such experiments should be conducted for a longer term, monitoring the temporal changes in soil properties during every season, so that the effect of seasonal variations over the years may be studied. Management practices which improve soil structure and consequently the hydraulic properties, like green
manuring and residue management of the previous crop, should be tested for their
temporal effect on $\theta_v$ and soil hydraulic properties.

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Chapter 4

Comparison of the temporal variation in soil physical and hydraulic properties under different tillage and irrigation management between wheat and maize

4.1 Abstract

Experiments were conducted to investigate the effects of three tillage practices (Cultivator, Moldboard plow and Chisel plow) and two irrigation techniques (Flood and Sprinkler) on soil physical properties and temporal variations in soil hydraulic properties in wheat-maize cropping system. The tillage and irrigation treatments implemented for the wheat crop were repeated for the subsequent maize crop restoring the same layout plan. Moldboard plow resulted in significantly higher yield in wheat and maize followed by chisel plow and cultivator, while the effect of irrigation techniques was not significant. The hourly monitoring of volumetric soil water content ($\theta_v$) dynamics showed that the decrease in $\theta_v$ during drying after irrigation was greater in wheat than in maize, greater in flood than in sprinkler irrigation and greater in moldboard plow than in chisel plow and cultivator. Soil bulk density ($\rho_b$), as determined from the core samples taken before irrigations in wheat and at the end of crop season in maize, was lower during wheat than after maize. The major differences in $\theta_v(\psi_m)$ between the two crops were primarily due to the time of core sampling. Plant available water capacity ($\theta_{PAWC}$) was greater in maize than in wheat and cultivator had the highest $\theta_{PAWC}$. Wheat had
greater volume of transmission pores ($> 10 \mu m, \varphi_{>10}$), whereas extraordinary rains and irrigations after tillage reduced these larger pores in maize. Field saturated hydraulic conductivity ($K_{fs}$) determined before irrigations and at the end of both crop seasons was greater in wheat than in maize. Moldboard plow exhibited greater $K_{fs}$ followed by chisel plow and cultivator in both crops and it decreased significantly with time in wheat but not in maize. Flood irrigation was responsible for a reduction in $K_{fs}$ and the effect was greater in wheat as compared to maize. It was clear from the studies that tillage systems change soil physical and hydraulic properties depending on their type and depth. High rainfall after tillage, as in maize, and irrigation techniques, especially flood irrigation revert these changes. Soil hydraulic properties may be optimized with the combination of suitable tillage and irrigation for efficient utilization of water resources.

4.2 Introduction

Tillage and irrigation are two of the most influential soil manipulations having transient effects on soil physical and hydraulic properties. Therefore, the resulting variability in these soil properties is dynamic in space and time. These soil properties are expected to vary even during a crop cycle, especially after tillage and irrigation or rain. Logsdon et al. (1993) concluded that within-season changes in infiltration rates could be greater than the management-induced differences and suggested that the rate measurements should be recorded soon after tillage and irrigation or rainfall events. More recently, Bamberg et al. (2011) documented that high soil water contents after irrigation events followed by drier soil conditions resulting from large rates of
evapotranspiration modified soil physical and hydraulic properties throughout the crop production season. Changes in soil physical and hydraulic properties due to tillage are reverted back to the original state as a result of natural reconsolidation due to wetting and drying cycles (Green et al., 2003) created by rain events or supplementary irrigation provided to the crops. The reconsolidation is a dynamic process and it may depend on the frequency (Cameira et al., 2003), amount (Bandaranayake and Arshad, 2006) and method (Bandaranayake et al., 1998) of water application and subsequent drying. Consequently, the coupled effects of tillage and irrigation management are responsible for temporal variability in soil physical and hydraulic properties and processes. Information available in the literature about short-term tillage-induced effects on the hydro-physical properties of agricultural soils and their dynamics is very scarce (Green et al., 2003).

Type of crop can affect soil water distributions and soil hydraulic properties either directly by root water uptake (Feddes et al., 1988; Zhuang et al., 2001) or indirectly by modifying the soil pore structure through the growing root system (Angers and Caron, 1998; Kodešová et al., 2006; Rasse et al., 2000). The crop plants varying in root systems and water requirements may affect soil physical and hydraulic properties differently. Wheat has a concentrated type of root system with a greater number of nodal roots densely distributed, compared to maize which has a scattered type of root system with fewer but longer nodal roots, many of which run obliquely and vertically in the soil profile (Grzesiak, 2009).
Many studies have focused on the impact of tillage practices on soil physical and hydraulic properties, while fewer have been conducted on the influence of different irrigation systems on soil properties. Studies that have investigated the combination of tillage and irrigation are even fewer. Experiments were conducted with an objective to compare the effect of tillage practices and irrigation techniques on seasonal temporal variability of soil water content and physico-hydraulic properties in wheat and maize crops grown on the same plots.

4.3 Materials and Methods

This experiment was conducted during 2009-10 to investigate the effect of different tillage and irrigation techniques on temporal variability of soil physical and hydraulic properties in wheat-maize cropping systems at the experimental area of National Agricultural Research Centre (NARC), Islamabad, Pakistan. The details about the soil classification and physical properties along with the climate of the area have been mentioned earlier (Section 2.3). The rainfall along with daily maximum and minimum air temperatures during the growing seasons of both crops is presented in Figure 4.1.

4.3.1 Experimental Treatments and Layout

Three tillage methods (Cultivator, moldboard plow and chisel plow) and two irrigation techniques (Flood and sprinkler irrigation) were laid out in a split block design with four
replications. Details regarding the tillage operations and irrigation techniques along with the resulting treatment combinations have been discussed in Section 2.3.1.

Figure 4.1: Daily rainfall and maximum and minimum temperatures recorded during the growing seasons of wheat (2009-10) and maize (2010) at a meteorological station located 1 km (aerial distance) from the experimental field.

The tillage and irrigation treatments implemented for the wheat crop according to the layout plan (Figure 2.2) were repeated for the subsequent maize crop maintaining the same layout. The proper soil moisture for tillage operations was lacking due to a long dry spell before wheat was planted requiring the application of pre-sowing flood irrigation (7.5 cm water depth), while it was not needed for maize as it had already received 76 mm of rain during the last month (Figure 4.1). Half of the recommended dose of N (60 and 75 kg ha$^{-1}$) as urea and full recommended doses of P (100 and 90 kg ha$^{-1}$) as triple superphosphate and K (75 and 50 kg ha$^{-1}$) as sulphate of potash were broadcast as a starter dose of fertilizer to wheat and maize crops, respectively. Wheat
(Triticum aestivum L. variety: Wafaq-2001) was seeded (160 kg ha\(^{-1}\)) with a wheat drill at row-to-row distance of 25 cm. Maize sowing was delayed for a month due to heavy spell of monsoon rains (Figure 4.1) starting the day following tillage operations which required switching to a short duration, late variety of maize (Zea mays L. variety: Swan-3). It was planted with a maize planter keeping a row-to-row distance of 75 cm and plant-to-plant distance of 20 cm. Tillage operations followed by wheat sowing were done in the last week of December 2009, while for maize, tillage was carried out in the third week of July 2010 and its planting after one month. The second half of nitrogen fertilizer was top dressed for both crops two months after germination.

Methods regarding irrigation techniques have been discussed in Section 2.3.2. One each of flood (7.5 cm depth of water) and sprinkler irrigation (5 cm depth of water) was applied to the respective plots of wheat and maize crops at their critical grain filling and blister stages, respectively. Irrigations at earlier critical stages were not needed in both the cases due to enough moisture in soil resulting from rains (Figure 4.1) at those stages. Tensiometer based evaluation also did not show a need for irrigation at those stages. Flood and sprinkler irrigations were applied to wheat in the second week of April 2010 and to maize in second and third weeks of November 2010, respectively.

4.3.2 Monitoring Soil Water Content and Soil Temperature

Volumetric soil water content, \(\theta_v\) (m\(^3\) m\(^{-3}\)), and soil temperature (\(^\circ\)C) were monitored hourly at 10 and 20 cm depths in every treatment combination in two of the four replication blocks during wheat and maize cropping seasons using water content
reflectometers (WCR) model CS616 and type-T (copper-constantan) thermocouples (Section 2.3.3), respectively, installed at the same location within each plot, as much as practical, for both crops. The monitoring of $\theta_v$ and soil temperature was started 67 days after tillage and continued for 90 days during wheat season, while it started 111 days after tillage and lasted for only 40 days through the maize season.

4.3.3 Monitoring Soil Water Potential

Pre-hydrated tensiometers were installed within 1 m and at the same depths as WCRs and thermocouples keeping the centre of each ceramic cup at the desired depths as close as practical. They were installed in the second week of March 2010 for wheat and in the first week of November 2010 for maize. Total pore water potential ($\psi_m$) was recorded directly with a digital Tensimeter as close to twice a week as possible.

4.3.4 Determination of Field Saturated Hydraulic Conductivity

Quasi-steady flow rate ($L^3 T^{-1}$) out of the cylinder of a Guelph Pressure Infiltrometer (GPI) attached to a Guelph Permeameter (GP) reservoir (Soil Moisture Equipment Corp., Santa Barbara, CA, USA) at a single ponding depth (10 cm) was measured from all treatment combinations in two replications. The measurements were carried out 13 and 21 weeks after tillage operations for wheat and 17 and 23 weeks after tillage operations for maize according to the method described in Section 2.3.4. The former events were before the irrigations and the latter after the irrigations in both the crops. Field saturated hydraulic conductivity, $K_{fs}$ (cm h$^{-1}$), was calculated taking the
value of macroscopic capillary length parameter ($\alpha^*$) as 0.12 cm$^{-1}$, which is appropriate for agricultural soils (Reynolds, 2008a, b).

### 4.3.5 Determination of Soil Water Retention Characteristics and Bulk Density

Intact soil cores (5 cm internal diameter and 2.5 cm length) were collected (Section 2.3.6) from 10, 20 and 30 cm depths from all treatment plots in two replications during wheat and maize growing seasons. The cores were collected in the 1st week of April 2010, before irrigating the wheat crop and in the 1st week of December 2010, after harvesting the maize crop. Water satiated cores were placed on pre-saturated porous ceramic plates of appropriate bubbling pressure and subjected to $-30$ ($\psi_{FC}$), $-100$ ($\psi_{100}$), $-500$ ($\psi_{500}$), $-1000$ ($\psi_{1000}$) and $-1500$ ($\psi_{PWP}$) kPa of matric pressures, $\psi_m$, using pressure-plate extractors (Soilmoisture Equipment Corp., Santa Barbara, CA, USA). Gravimetric water content was determined at all $\psi_m$ and used to calculate $\theta_v$ (m$^3$ m$^{-3}$) at each $\psi_m$, soil bulk density, $\rho_b$ (Mg m$^{-3}$), total soil porosity, $\varphi$, plant available water capacity, $\theta_{PAWC}$, and the volume of pores belonging to six diameter classes, i.e. $<0.2$ μm ($\varphi_{<0.2}$), 0.2-0.3 μm ($\varphi_{0.2-0.3}$), 0.3-0.6 μm ($\varphi_{0.3-0.6}$), 0.6-3 μm ($\varphi_{0.6-3}$), 3-10 μm ($\varphi_{3-10}$) and $>10$ μm ($\varphi_{>10}$).

### 4.3.6 Statistical Analysis

#### 4.3.6.1 Temporal Stability of Soil Water Content

Temporal persistence of the relative differences in soil water content and their stability as affected by different soil management practices applied in the experimental field was evaluated separately before and after irrigation events for both crops using the
approach of Vachaud et al. (1985) extended further to include measurements made at different depths (Hu et al., 2010). An unequal number of hourly observations recorded for flood and sprinkler irrigations as a result of different days of their application instigated a separate analysis for both irrigation techniques. Consequently, replication-averaged measurements at all times for three tillage treatments and two depths were used to calculate time averaged relative difference ($\bar{\delta}_{ij}$) of soil water content and its standard deviation ($\sigma(\bar{\delta}_{ij})$) as discussed earlier (Section 2.3.7.1).

4.3.6.2 Analysis of Variance

The data were subject to variance analyses with SAS software version 9.1 (SAS Institute Inc., Cary, NC, USA) using Proc Mixed model. The parameters determined were handled according to their structure. Block, tillage and irrigation were taken as classification variables for all parameters and depth, time, pressure heads and pore classes as non-randomized repeated measures for the respective parameters (Section 2.3.7.2).

4.4 Results and Discussion

4.4.1 Yield Parameters

Grain and straw yield in wheat (Table 2.1) as well as grain and stover yield in maize (Table 3.1) were significantly affected by tillage practices but not by irrigation techniques. Moldboard plow had the highest yield in both crops with the difference in maize being significant with all other tillage types and in wheat with the cultivator only.
It had 14 and 12% higher grain and straw yield in wheat, respectively, while 21 and 23% higher grain and stover yield in maize, respectively, than those of cultivator. The interactive effect of moldboard was better with sprinkler irrigation in both the crops. Higher yield in moldboard plow was attributed to the lower $\rho_b$ and higher $\varphi$ with moldboard plow in both crops (Tables 2.2 and 3.2) and the resulting greater root growth and water uptake (Chaudhary et al., 1985).

4.4.2 Soil Water Content

Wheat was planted in the last week of December 2009 after attaining proper moisture condition for tillage and sowing, as a result of the flood irrigation (7.5 cm water depth) applied a couple of weeks earlier. The monitoring of volumetric soil water content ($\theta_v$) started a couple of months after sowing, wherein the first month did not have any rain, while the second month received 82 mm of rain. Less pan evaporation (average $< 2$ mm day$^{-1}$) due to low terrestrial temperature (average minimum of 6.4°C and average maximum of 19.5°C) caused $\theta_v$ to start off higher in the monitoring period (Figure 2.3). The weather conditions were quite different in the case of maize. Tillage practices for maize planting were carried out two months after wheat harvesting and during this period, 106 mm of rainfall was received especially close to the tillage time. Although the terrestrial temperature was higher (average minimum of 21°C and average maximum of 37°C) than that in the case of wheat at this stage, yet the soil had proper moisture for tillage, so irrigation was not needed. A heavy spell of monsoon rains following the tillage constrained the sowing to be delayed for a month. Consequently,
the monitoring of $\theta_v$ was started more than three months after tillage and until then it had received 775 mm of rain with 511 mm in the first month. The last month before the start of the monitoring period received only 32 mm of rain resulting in lower $\theta_v$ (Figure 3.2) than that in the case of wheat in the beginning despite the fact that it had received a lot of rain in the past. The wheat crop continued to receive showers from time to time during the course of its season but the maize crop had only one event of 4 mm rain. The changes in $\theta_v$ were observed in the beginning of monitoring during wheat season in response to even a 3-4 mm of rain but during maize season, the single rain went almost unnoticed. This may be related to the lower temperatures and higher $\theta_v$ in the start of wheat season than those in maize season. The patterns of soil drying in the beginning of the monitoring periods before irrigations showed that the decline in $\theta_v$ with time was greater in wheat than in maize in all the treatments and the effect was more at 10 cm than at 20 cm depth. The drying pattern was similar for 10 cm and 20 cm depths in the case of maize. So, the soil was drying quicker in wheat than in maize at both depths especially closer to the surface. The $\theta_v$ was higher at 20 cm than at 10 cm depth during drying for both crops.

Tillage practices and irrigation techniques affected the $\theta_v$ differently in wheat and maize crops. Flood and sprinkler irrigations caused $\theta_v$ to increase quickly, with a greater surge in the case of flood irrigation at 10 cm than at 20 cm depth for both crops. The comparison between crops showed that the increase in $\theta_v$ in response to both types of irrigation was greater in wheat at 10 cm depth, while it was higher in maize at 20 cm depth. The increase in $\theta_v$ resulting from both the irrigations particularly after
flood irrigation was greater with moldboard plow followed by chisel plow and cultivator in both crops. Moldboard and chisel plow showed higher $\theta_v$ at 20 cm depth after flood irrigation in both crops due to their similarity in the depth of cultivation. The higher $\theta_v$ in moldboard plow especially after flood irrigation corresponds to the higher total porosity in this case (Table 2.2 and 3.2).

The drying trend after flood and sprinkler irrigations was not similar for wheat and maize crops. The decrease in $\theta_v$ during drying after flood irrigation was quicker at 10 cm depth especially in wheat. Although the drying was slower in sprinkler irrigated wheat, yet it was still faster than that in the case of maize at both depths. Since maize did not get any more water, it attained a similar and consistent drying pattern a few days after irrigation as it had before irrigation. Contrastingly, the wheat crop continued to receive rain responsible for the rises in $\theta_v$ followed by the declines on drying. The surge in $\theta_v$ as well as the rapidity of declines were proportional to the water received until the irrigations were applied. Afterwards, the magnitude of rises and rapidity of declines were reducing every time. Faster drying in wheat may be ascribed to the higher porosity due to lesser soil reconsolidation after tillage until the irrigations were applied, while maize had already received a huge amount of rainfall resulting in more reconsolidation reducing the soil porosity. Higher porosity may be related to faster water movement from shallower depth to deeper depth. The rapid decrease in water content may be attributed to higher field saturated hydraulic conductivity (Figure 2.8 and 3.7) and greater water transmission pores (Table 2.3 and 3.3) in the respective crops. The comparison amongst the tillage treatments revealed that the drying right
after flood and sprinkler irrigations was faster initially in the case of moldboard plow especially at 10 cm depth and more in flood irrigated wheat than in maize with both irrigation types. Consequently, all the tillage treatments had similar $\theta_v$ at 10 cm depth about a day after flood irrigation. The faster drying with moldboard plow after flood irrigation in wheat corresponds to its higher $K_{fs}$ (Figure 2.8 and 3.7) and greater proportion of water conducting pores (Table 2.3 and 3.3) resulting in the faster movement of water from shallower depth to greater depth.

Diurnal variations in $\theta_v$ for both crops were associated with the soil temperature (Figure 2.5 and 3.4) and its fluctuations (Evett et al., 2011). They were higher at 10 cm than at 20 cm depth corresponding to the higher temperature fluctuation closer to the surface in both crops. They were greater in wheat than in maize conforming to higher soil temperature as well as its greater fluctuation in wheat (Lowest 11° and highest 42°C) than in maize (Lowest 6° and highest 25°C). These variations remained consistent during the growth period of maize but they increased with the rising soil temperature during the growth period of wheat at a particular depth. Sprinkler irrigation was responsible for greater diurnal variations in $\theta_v$ during the last three weeks of monitoring period in wheat, while the type of irrigation did not affect the diurnal variations in maize.

Temporal variability in $\theta_v$ was greater during wheat as compared to that in maize season (Figure 2.4 and 3.3). Temporal stability of $\theta_v$ decreased with the flood irrigation in both crops. The greater depth had temporally more stable $\theta_v$ in wheat, while the reverse occurred in maize for all tillage and irrigation treatments before and after
irrigation. Spatial patterns of the temporal soil water content in wheat revealed that cultivator plots remained drier after flood irrigation and wetter after sprinkler irrigation with a reverse trend for moldboard and chisel plow at 10 cm depth, while there was no change in the trend for different tillage treatments and irrigation techniques at both depths in maize.

4.4.3 Soil Temperature

Fluctuation in temperature of the soil under different tillage practices and irrigation techniques at two depths indicated an overall increasing trend during the wheat monitoring period (Figure 2.5), while a decreasing trend during the maize period (Figure 3.4) corresponding to the variation in terrestrial temperature (Figure 4.1). Diurnal variations were more pronounced at 10 cm depth than at 20 cm depth for both crops with variation increasing towards the end of the season in wheat as the terrestrial temperature was rising. Tillage practices, irrigation techniques and rain events did not seem to affect the soil temperature in both crops. Temporal stability of soil temperature for all tillage types decreased with flood irrigation at both depths, while it decreased with sprinkler irrigation only at 10 cm and not at 20 cm depth in both crops (Appendix I and II). Although, the temporal stability of soil temperature was generally not different for wheat and maize crops, its variability was greater in maize as compared to the wheat crop.
4.4.4 Soil Bulk Density and Total Porosity

Soil core sampling for the determination of water retention characteristics and bulk density ($\rho_b$) was done in the middle of the growing season before irrigation in wheat, but it was done at the end of the growing season in maize resulting in lower measured soil reconsolidation after tillage in the wheat as compared to the maize crop. Consequently, greater overall $\rho_b$ was observed in the maize (Table 3.2) than that in the wheat crop (Table 2.2). The main effects of tillage and irrigation were not significant at $\alpha = 0.05$, while that of depth was significant in both crops. Bulk density increased significantly with depth, causing $\varphi$ to decrease, in both crops. As $\rho_b$ was determined before irrigation in wheat, the values observed for flood and sprinkler irrigations were similar in contrast with the case of maize where $\rho_b$ was higher and the resulting $\varphi$ was lower under flood irrigated plots. The interaction between tillage practices and soil depth was significant in the wheat but not in the maize crop. Moldboard plow had significantly lower $\rho_b$ and higher $\varphi$ than that of the cultivator and chisel plow at 10 cm depth with a similar but more pronounced effect at 20 cm depth in wheat. The trend was similar in the case of maize with higher values of $\rho_b$ and lower values of $\varphi$, but not significant statistically. The difference of $\rho_b$ and $\varphi$ between 10 cm and 20 cm depths was lower in the case of moldboard and chisel plow as compared to the cultivator corresponding to their depth of cultivation. The differences in the effects of tillage practices at different depths on $\rho_b$ and $\varphi$ in wheat and their similarities in maize may be attributed to the long and heavy spell of monsoon rains after tillage in maize responsible
for the cycles of wetting and drying resulting in reconsolidation (towards original) of the soil loosened by the tillage practices (Green et al., 2003).

### 4.4.5 Soil Water Retention

Soil water retention was generally higher in maize (Figure 3.5) than that in wheat (Figure 2.6), with greater retention at 10 cm depth versus 20 cm depth for both crops. Tillage practices and irrigation techniques as main effects on soil water retention characteristics ($\theta_v(\psi_m)$) were not significant statistically, while those of soil depth and matric pressure ($\psi_m$) were significant at $\alpha = 0.05$ in wheat and maize crops. The water retained ($\theta_v$) at 10 cm and 20 cm depths was similar in both crops but it was significantly higher in wheat and lower in maize as compared to that at 30 cm depth. The $\theta_v$ at various $\psi_m$ significantly decreased with decreasing $\psi_m$ in both crops having higher values in maize especially at higher $\psi_m$ ($\psi_{FC}$ and $\psi_{100}$). Noticeable differences in $\theta_v(\psi_m)$ for all tillage practices and irrigation techniques were observed at 10 and 20 cm depths especially at higher $\psi_m$ ($\psi_{FC}$ and $\psi_{100}$ for wheat; $\psi_{FC}$, $\psi_{100}$ and $\psi_{500}$ for maize). At 30 cm depth, the $\theta_v(\psi_m)$ for all tillage and irrigation treatments at all matric pressures was lower in wheat and higher in maize than the shallower depths. In addition, there was no difference between the tillage and irrigation treatments at this depth in both crops.

The major differences in $\theta_v(\psi_m)$ between the two crops were primarily due to the time of core sampling for water retention characteristics. As the sampling in the wheat season was done before irrigation and in the maize season after irrigation, the
effect of irrigation on $\theta_v(\psi_m)$ is evident in maize for various tillage operations at different depths. The $\theta_v(\psi_m)$ was similar for the flood and the sprinkler irrigations in wheat, while it was significantly lower in the sprinkler than the flood irrigation in maize, under different tillage practices at 10 cm and 20 cm depths. So the differences in $\theta_v(\psi_m)$ in wheat were only due to tillage and depth, while the effects of irrigation techniques were also included in maize. Cultivator, closely followed by the chisel plow, had significantly higher $\theta_v$ than the moldboard plow at $\psi_{FC}$ and $\psi_{100}$ but it was similar for both irrigation types in wheat and at $\psi_{FC}$, $\psi_{100}$ and $\psi_{500}$ but significantly lower for sprinkler irrigation than that of the flood irrigation in maize at 10 cm depth. Thus the added effects of sprinkler irrigation to the moldboard plowing caused the lowest water retention, while those of flood irrigation to the cultivator caused the highest water retention in maize especially at higher $\psi_m$. The trend of $\theta_v$ was similar within tillage treatments at 20 cm depth but the chisel plow had lower $\theta_v(\psi_m)$ than that at 10 cm depth in both crops. The similarity in the behavior of the cultivator and the chisel plow at 10 cm depth may be related to their strong similarity in the type of soil manipulation. Moldboard plow had greater volume of transmission pores in wheat (Table 2.3) as well as in maize (Table 3.3) causing higher field saturated hydraulic conductivity in both crops (Figure 2.8 and 3.7, respectively) resulting in lower water retention. The close resemblance of water retention in chisel and moldboard plow at 20 cm depth may be due to their deeper depth of cultivation.

The relationship between $\theta_v$ (from WCRs) and $\psi_m$ (from tensiometers) as observed twice a week in the field throughout wheat (Figure 2.7) and maize (Figure 3.6)
growing seasons revealed that the $\psi_m$ mostly remained from $-80$ to $-25$ and $-65$ to $-25$ kPa in wheat and maize, respectively, showing that soil matric potential persisted at the higher end of plant available water range during both crop seasons. The $\theta_v$ was generally lower at 10 cm depth than at 20 cm depth for all tillage and irrigation treatments in wheat, while it was true for only moldboard plow for both types of irrigation in maize. This might be due to higher $\varphi_{>10}$ at 10 cm depth (Table 2.3 and 3.3) draining easily into 20 cm depth with lower $\varphi_{>10}$. The relationship shows a scattered pattern in wheat, probably due to overlap of many wetting and drying cycles. This may be attributed to the frequent rain events distributed over the wheat season. The trend of $\theta_v(\psi_m)$ was more typical in flood irrigated plots for all tillage types especially in maize, due to a single drying cycle.

4.4.6 Plant Available Water Capacity

Plant available water capacity ($\theta_{PAWC}$) was generally greater in maize (Table 3.2) as compared to the wheat crop (Table 2.2). The main effect of tillage was significant in wheat but not in maize, while those of irrigation and depth were not significant in both the crops. Cultivator had significantly higher $\theta_{PAWC}$ than that in moldboard plow and the chisel plow was not significantly different from other tillage types in wheat. The interaction between tillage and depth was significant in wheat, elucidating that cultivator had significantly higher $\theta_{PAWC}$ only at 10 cm and 20 cm depths followed by chisel and moldboard plows. The differences between $\theta_{PAWC}$ at 10 cm and 20 cm depths were lower in wheat than in maize for all combinations of tillage and irrigation.
4.4.7 Pore Size Distribution

The size distribution of pores in various diameter classes was determined in the middle of the wheat season before irrigation events, while it was determined at the end of the maize season. So the pore size distribution included the effect of irrigation techniques in the case of maize but not in wheat. There was a significant variation in the volume of pores occupied by different pore diameter classes in wheat (Table 2.3) as well as in maize (Table 3.3). The pores < 0.2 μm in diameter (φ<0.2, pores containing unavailable water) occupied most of the volume followed by the pores > 10 μm in diameter (φ>10, freely draining pores) in both crops. These pore classes comprised about 70 and 60% of the total pores, respectively, leaving only about 30 and 40% of the pores capable of holding water in wheat and maize, respectively. The major difference was in the φ>10, where wheat had greater volume of pores (0.16 m³ m⁻³) than that of the maize (0.06 m³ m⁻³). The volume of pores of other size classes was similar in both crops. This indicates that the extraordinary rains and irrigations after tillage caused the larger pores (φ>10) to decrease in maize. The interactive effect of tillage × pore class revealed that moldboard plow had significantly higher φ>10 followed by chisel plow and cultivator, while that of depth × pore class explicated that the φ>10 as well as φ<0.2 were significantly higher at 10 cm depth followed by 20 cm and 30 cm depths in both the crops with higher magnitude of the φ>10 in wheat.

The three way interaction between tillage × depth × pore class further explained that the moldboard plow had significantly higher volume of transmission pores (φ>10) at 10 cm and 20 cm depths than that of chisel plow with the similar φ>10 at both depths
but higher than that at 30 cm depth for the respective tillage types, while the $\varphi_{>10}$ was not different at all depths in the case of cultivator in wheat as well as in maize. The $\varphi_{<0.2}$ was not affected by different combinations of tillage and irrigation at all depths in wheat as well as in maize with similar magnitude in both crops. It was evident that the effect of moldboard and chisel plow on $\varphi_{>10}$ extended down to 20 cm depth with moldboard having greater effect. The interaction between irrigation $\times$ depth $\times$ pore class revealed that the sprinkler irrigation had significantly higher $\varphi_{>10}$ than that of flood irrigation at 10 cm depth in maize, thus responsible for reducing the volume of water transmission pores.

4.4.8 Field Saturated Hydraulic Conductivity

Field saturated hydraulic conductivity ($K_{fs}$) was generally greater in wheat (Figure 2.8) than that in maize crop (Figure 3.7) especially in the first determination before irrigation. The changes in $K_{fs}$ between the first and the second determinations were a result of 92 mm of rain in addition to the irrigations applied in wheat, while only the flood and sprinkler irrigations in maize. The main effect of tillage was significant with moldboard plow exhibiting greater $K_{fs}$ followed by chisel plow and cultivator in both the crops. Irrigation techniques did not significantly affect the $K_{fs}$ in both the crops, while it decreased with time significantly in wheat but not in maize. The determination of $K_{fs}$ in maize season was started after a long and heavy spell of monsoon rains causing the decrease in water transmission pores ($> 10 \mu m$, Section 4.4.7) due to soil reconsolidation after tillage (Green et al., 2003) resulting in the decreased $K_{fs}$ even at
the first determination event (17 WAT) and responsible for statistically similar $K_{fs}$ with the second event (23 WAT). The interactive effect of irrigation and time was also significant in wheat but not in maize. The $K_{fs}$ was significantly higher after the sprinkler as compared to the flood irrigation (21 WAT) in wheat with similar but not significant trend in maize due to less soil reconsolidation with tillage after sprinkler irrigation especially in wheat. The three way interaction between tillage, irrigation and time was also significant in wheat and not in maize. Flood irrigation was responsible for a greater decrease in $K_{fs}$ where moldboard plow was applied followed by chisel plow and cultivator, while sprinkler irrigation caused a lower decrease in $K_{fs}$ similarly in all tillage types in both crops with higher magnitudes in wheat. Despite the fact that wheat crop received 92 mm of rain in addition to the irrigation events between the first and the second determinations, the $K_{fs}$ decreased more with flood irrigation than the sprinkler irrigation. In contrast, the maize crop had already received 802 mm of rain before the first determination, probably responsible for much of the soil reconsolidation and decrease in $K_{fs}$; it still decreased as a result of both the irrigation types with greater magnitude in the case of flood irrigation.

### 4.5 Conclusions

Comparison of the two studies on temporal variation in soil physical and hydraulic properties under different tillage and irrigation management between wheat and maize concluded that the tillage implements change the soil properties depending on their type and depth of influence. A major difference between the two experiments
was the rainfall pattern. Wheat season received 199 mm of rain scattered throughout
the crop growth period, while maize received 672 mm of rain in just forty days after
tillage operations. Secondly, core sampling for the determination of $\rho_b$, $\varphi$, $\theta_v(\psi_m)$,
$\theta_{PAWC}$ and pore size distribution was done in the middle of wheat crop season before
any irrigations, while it was done at the end of the maize season.

The rains caused most of the soil reconsolidation, generally increasing $\rho_b$ and
decreasing $\varphi$ in maize. The significantly lower $\rho_b$ corresponding to the higher $\varphi$ up to 20
cm depth in moldboard plow in wheat and non-significant differences in maize indicated
that the changes induced by tillage were reverted back to original state to a greater
extent in maize than wheat. It was related to the heavy load of rainfall responsible for
soil settling in maize. The $\varphi_{>10}$ was significantly higher in moldboard plow resulting in
higher $K_{fs}$ in both crops than the other two tillage treatments. Flood irrigation caused a
higher increase in $\theta_v$ than sprinkler irrigation in all tillage treatments but it drained
quicker in moldboard plow after flood irrigation in both crops. It was concluded from
these facts that the larger pores created, to a greater magnitude, by moldboard plow
were less affected by rains in wheat as well as in maize. Although CS616 was able to
monitor the changes in $\theta_v$, it exhibited high diurnal variations especially at higher
temperatures creating doubts about the absolute values of $\theta_v$ but it can effectively be
used for comparative studies in the field.

The $\theta_{PAWC}$ was lower in moldboard plow as compared to chisel plow and
cultivator in wheat, while it was similar for all tillage treatments in maize. Even then, the
yield parameters were higher for moldboard plow in both crops revealing that $\theta_{PAWC}$ is
not the only factor responsible for better yields. The higher yields were attributed to better root growth in more porous soil and resulting water uptake. Water retention at matric pressures slightly higher than $\psi_{FC}$ ($\sim 10$ kPa) may help to quantify the pores slightly larger than 10 $\mu$m (but smaller than 30 $\mu$m), which transmit water very slowly and may still be useful for plant uptake.

The greater decrease in $K_{fs}$ with flood irrigation than sprinkler irrigation especially after moldboard plowing in both crops despite the huge rains after tillage in maize demonstrated that soil reconsolidation after tillage is greater with flood irrigation as compared to sprinkler irrigation and moldboard plow is more prone to this soil process. The reconsolidation continued even after the large downpours. The combination of moldboard plow and sprinkler irrigation exhibited the least soil settlement.

Management practices which improve soil structure and consequently the hydraulic properties, like green manuring and crop residue management, may be tested for their temporal effect on $\theta_v$ and soil hydraulic properties. Various crop rotations produce different quantities and qualities of roots and residues responsible for variation in soil physical and hydraulic properties. Temporal effects of different crop rotations on these soil properties should also be included in the studies conducted in future.

4.6 References


Chapter 5

Summary, overall conclusions and recommendations

5.1 Summary and conclusions

This research was carried out with the following objectives:

1. To measure the effect of different tillage practices and irrigation techniques on soil physical and hydraulic properties during individual wheat and maize crop seasons.

2. To compare the temporal changes in soil hydraulic properties after tillage and in response to irrigation between wheat and maize crops grown in successive seasons on the same experimental plots.

Field experiments were undertaken to investigate the effect of three tillage practices (Cultivator, moldboard plow and chisel plow) and two irrigation techniques (Flood and sprinkler irrigation) on temporal variation of soil physical and hydraulic properties in wheat and maize crops. The tillage implements changed the soil physical and hydraulic properties depending on their type and depth of influence, while irrigation techniques contribute differently depending on the mode of application. The difference in rainfall pattern of the two crop seasons was also responsible for the variation in soil properties. Wheat season received 199 mm of rain scattered throughout the crop growth period, while maize crop received 672 mm of rain in just forty days.
following tillage operations. The second source of differences between crop seasons was that the determination of \( \rho_b, \varphi, \theta_v(\psi_m), \theta_{PAWC} \) and pore size distribution was done in the middle of the wheat crop season before any irrigations, whereas it was done at the end of the maize season. Thus, the parameters measured include the effect of some rains in wheat, while they include the effects of considerable rains as well as irrigation treatments in maize.

The rains as well as irrigations caused most of the soil reconsolidation, generally increasing \( \rho_b \) and decreasing \( \varphi \) in maize. Moldboard plow had significantly lower \( \rho_b \), corresponding to the higher \( \varphi \) up to 20 cm depth than chisel plow and cultivator in wheat, while the differences were not significant in maize. This explained that the heavy loads of rainfall and irrigations were responsible for most of the soil settling, reverting the changes induced by tillage back to original state in maize but not in wheat for which measurements were done before irrigation. However, \( \varphi_{>10} \) was significantly higher in moldboard plow than other tillage treatments resulting in higher \( K_{fs} \) in both crops. In maize, the higher volume of larger pores in moldboard plow, despite the greatest soil reconsolidation, was related to better root growth and biological activity by the end of crop season. Flood irrigation caused a higher increase in \( \theta_v \), monitored throughout the crop season, than sprinkler irrigation in all tillage treatments but it drained quicker in moldboard plow after flood irrigation in both crops. It was concluded from these facts that the larger pores created, to a greater magnitude, by moldboard plow were less affected by rains in wheat. Although the larger pores were generally lower in maize, the effect of rains and irrigation treatments was less pronounced in moldboard plow.
Although CS616 was able to monitor even very small changes in $\theta_v$ in response to rain events, it exhibited high diurnal variations (Evett et al., 2011), especially at higher temperatures creating doubts about the absolute values of $\theta_v$ but it can effectively be used for comparative studies in the field.

The $\theta_{PAWC}$ was generally higher in maize as compared to wheat. It was obvious that the rains and irrigations in maize caused water transmission pores to decrease and those that retain water in plant availability range to increase. The $\theta_{PAWC}$ was lower in moldboard plow as compared to chisel plow and cultivator in wheat, whereas it was similar for all tillage treatments in maize. Even then, the yield parameters were higher for moldboard plow in both crops revealing that $\theta_{PAWC}$ is not the only factor influencing yield. The $\theta_v$ remained mostly in the plant availability range in all the treatments throughout the growing seasons for both crops, overturning the effects of variability in $\theta_{PAWC}$. The higher yield under moldboard plowing was attributed to better root growth in more porous soil and resulting water uptake.

The $K_{fs}$ was generally higher in the wheat as compared to the maize crop, corresponding to the higher $\varphi_{>10}$. The $K_{fs}$ decreased with time in both crops with a greater magnitude in wheat. Similarly, the magnitude of decrease in $K_{fs}$ with time was greater in moldboard plow than chisel plow and cultivator and also with flood irrigation than sprinkler irrigation. The greater decrease in $K_{fs}$ with flood irrigation than sprinkler irrigation especially after moldboard plowing in both crops despite the huge rains after tillage in maize demonstrated that soil reconsolidation after tillage is greater with flood irrigation as compared to sprinkler irrigation and moldboard plow is more prone to this
soil process. It also explained that the soil reconsolidation process continued even after the large amounts of downpours and the combination of moldboard plow and sprinkler irrigation presented better soil physical and hydraulic properties.

5.2 Recommendations for future research

Management practices which improve soil structure and consequently the hydraulic properties like green manuring and crop residue management should also be tested for their temporal effect on $\theta_v$ and soil hydraulic properties. Such experiments should be conducted for a longer term, monitoring the temporal changes in soil properties during every season, so that the effect of seasonal variations over the years may be studied. Water retention at matric pressures higher than $\psi_{FC}$ may help to quantify the pores slightly larger than 10 $\mu$m, which transmit water very slowly and may still be useful for plant uptake. If core samples are collected at various times during a crop season, the patterns of temporal changes in soil physical and hydraulic properties after tillage can be monitored. In addition to that, variably saturated hydraulic properties measured at different times may give useful information about the transmission of water through different sized pores.

5.3 References

Time averaged relative difference ($\delta_{ij}$) of soil temperature as affected by different tillage and irrigation management practices at two depths in wheat. Error bars represent the standard deviation ($\sigma(\delta_{ij})$).
Appendix II

Time averaged relative difference ($\delta_{ij}$) of soil temperature as affected by different tillage and irrigation management practices at two depths in maize. Error bars represent the standard deviation ($\sigma(\delta_{ij})$).
Field implements used in the experiment.
Appendix IV

Flood Irrigation

Cutthroat Flume

Rain-gun Sprinkler

Pumping System

Irrigation techniques used in the experiment.