University of Alberta

Changes in Soil Physical Properties Under Manure Application

by

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Abstract

Cattle manure applied to different soils in Alberta at different rates and durations led to changes in the soil properties organic matter, bulk density, water retention and infiltration. Changes to soil physical properties can be described by linear statistical equations, where changes to soil physical properties are functions of soil texture and net increases in organic matter. Based on changes in physical properties of soils receiving manure, a model for predicting sorptivity and wetting front potential during infiltration was developed and evaluated. This model requires saturated hydraulic conductivity and the initial and saturated water contents to estimate the wetting front potential and infiltration. The model is tested on a wide range of soils. Results are compared with three other methods found in the literature. This model provides estimates as good as the other methods, but does not require the extensive input information and calculation as the other methods do.

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Chapter 1

1.1 Introduction

The beef cattle feedlot industry contributes significantly to Alberta's agricultural economy. In 2001 there were 2.4 million beef feedlot cattle in Alberta, making up 72% of Canada's fed cattle inventory. Seventy percent of feedlot cattle in Alberta are concentrated in areas south of Calgary (Statistics Canada 2001). It is a significant challenge to minimize adverse effects on soil, water and air caused by the massive amount of manure that is produced.

Manure applied to the land is a valuable source of plant nutrients. Beyond supplying nutrients for plant growth, manure affects the physical properties of soils. Manure has been found to decrease soil bulk density (Sommerfeldt and Chang 1985), increase aggregate stability (Martens and Frankenberger 1992) and increase soil water retention (Unger and Stewart 1974), leading to a general improvement in soil quality. It has also been found that soil water infiltration rates increase with manure application (Martens and Frankenberger 1992).

Sites have been set up across Alberta by various organizations to study the effects of manure applications on soil properties and the effects on the environment associated with these applications (Olson and Howard 2000, unpublished). Many of the studies have focused on finding a balance between maximum manure loading capacity and negative environmental impact. The intent of this study is to examine the effects of cattle manure application on soil physical properties such as bulk density, aggregate stability, water retention and infiltration.

Data collected on soil hydraulic properties (infiltration and water retention) led to examination of the physics of infiltration and of models that predict infiltration, such as the Green and Ampt (1911) and Philip (1957) models. Both models require the parameter 'average wetting front potential' (H_f), and most current methods for the calculation of this parameter are based on the unsaturated hydraulic conductivity (K) – matric potential (h) relationship. The measurement of this relationship is time consuming, and significant errors can arise in its estimate. Therefore, a new model that limits the inputs to a few easily obtainable soil properties, i.e., water content (θ) and saturated hydraulic conductivity (K_s), was developed and evaluated.

The overall objective of this study was to examine the effects of cattle manure, applied at different rates and durations, on the physical properties of soils in three locations in Alberta (St. Vincent, Lethbridge and Breton). We were specifically interested in the effects that a change in soil organic matter content, due to manure application, has on the soil physical properties of bulk density, water retention, and aggregate stability. If changes to these properties did occur, it is expected that there will also be changes in infiltration rates. Once the effects of manure on soil physical properties were measured, statistical models relating changes in soil physical properties to soil texture and net changes in soil organic matter content were developed using combined data from the three sites. Also, a new model for estimating the wetting front potential during infiltration was evaluated by comparing it to other methods found in the literature. The effectiveness and accuracy of this model is determined by comparing it to numerical simulations and field measurements.

This thesis is divided into two sections. In the first section (chapter 2), the effects of cattle manure on soil physical properties were investigated and statistical equations were developed to predict the changes that occur. In the second section (chapter 3), a new model for estimating the H_f parameter to be used in infiltration models is developed and evaluated.

1.2 References

Green, W.H., and Ampt, G.A. 1911. Studies on soil physics: I. Flow of air and water through soils. J. Agr. Sci. 4: 1-24.

Martens, D.A., and Frankenberger, W.T. Jr. 1992. Modification of infiltration rates in an organic amended irrigated soil. Agron. J. 84: 707-717.

Barry, Olson., and Allan Howard. 2000. Phoshphorous mobility in soil landscape: A site-specific study. Unpublished.

Philip, J.R. 1957. The theory of infiltration: 1. The infiltration equation and its solution. Soil Sci. 83: 345-357.

Sommerfeldt, T.G., and Chang, C. 1985. Changes in soil properties under annual applications of feedlot manure and different tillage practices. Soil Sci. Soc. Amer. J. 49: 983-987.

Statistics Canada and Alberta Agriculture, Food and Rural Development. 2001. www.albertabeef.org. Oct 2003.

Unger, P.W., and Stewart, B.A. 1974. Feedlot waste effects on soil conditions and water evaporation. Soil Sci. Soc. Amer. Proc. 38: 954-958.

Chapter 2

Effect of Cattle Manure On Soil Physical Properties

2.1 Introduction

Livestock manure can benefit plants and soils beyond its ability to supply nitrogen, phosphorous, potassium and micronutrients (Sweeten and Mathers 1985). Manure contributes to soil organic matter content, lowering the bulk density (Sommerfeldt and Chang 1985), increasing aggregate stability (Martens and Frankenberger 1992), and increasing field capacity and permanent wilting point (Unger and Stewart 1974). Thus, the addition of manure promotes a general improvement in soil physical quality. With decreased bulk density and increased aggregation, soil water infiltration rates can also be increased (Martens and Frankenberger 1992).

The effects of cattle manure on soil has been well studied. The increase in soil organic matter content is dependant on factors such as the amount and duration of manure applied (Sommerfeld and Chang 1985) and soil texture (Darwish *et al.* 1995).

Sommerfeldt and Chang (1985) measured the organic matter content of a clay loam soil during 15 years of manure application. There was a significant positive correlation between the annual rate of manure applied and the increase in soil organic matter content at the 0-15 cm depth interval. The results were similar between irrigated and non-irrigated soils, indicating that soil moisture may not influence the accumulation of soil organic matter (Sommerfeldt and Chang 1988).

Darwish *et al.* (1995) noted that nondegradable components present in the added organic matter would be expected to accumulate in the soil over time if the rate of organic matter addition exceeds the rate of microbial degradation. Nondegradable components can also be produced by microbial action. They found that after applying a total of 289 Mg/ha of manure (dry weight) over 15 years, soil organic matter content was increased from 2.9-3.2% for a fine sandy loam and from 2.4-3.0% for a silt loam soil. They also found that 95% of the total organic matter applied had degraded over the application period.

Several studies show that soil bulk density decreases with increasing rates of manure application (Tiarks *et al.* 1974; Unger and Stewart 1974; Sommerfeldt and Chang 1986). Powers *et al.* (1975) proposed that this decrease in bulk density was a dilution effect that resulted from the mixing of added organic matter with the denser mineral fraction of the soil. Others have suggested that the decreased soil density was due to decreased particle density and higher porosity (Tiarks *et al.* 1974). Khaleel *et al.* (1981) reviewed data regarding organic waste applications and found a linear relationship between percent decrease in bulk density and net increase in soil organic matter content.

Increases in field capacity and permanent wilting point due to applications of cattle manure have been reported (Unger and Stewart 1974; Sommerfeldt and Chang 1986; Miller *et al.* 2002). Water retention of soils is determined by the volume and size of soil pores and by the surface area of soil solids. Water retention at high matric potentials (e.g., field capacity) depends primarily on the capillary effect and the pore size distribution, while water retention at lower matric potentials is due increasingly to adsorption and is influenced less by structure and more by the texture and specific surface area of the soil (Hillel 1982). If field capacity and wilting point are increased equally, plant available water holding capacity will not be increased. Previous studies have found that there is little change to plant available water holding capacity with the increased field capacity and wilting point due to a cattle manure application (Sommerfeldt and Chang 1986; Miller *et al.* 2002).

Tiarks *et al.* (1974) reported that the water stability of soil aggregates increased linearly when the soil organic carbon content was increased above 1.55% and that the geometric mean diameter of water stable aggregates increased exponentially as the amount of manure applied increased. Unger and Stewart (1974) found that high feedlot waste applications lowered the percentage of small aggregates and raised the percentage of large aggregates.

The ability of soils to transmit water depends on the size, arrangement, and stability of the soil pores (Martens and Frankenberger 1992). Soil infiltration rate is a principal factor in determining the amount of runoff resulting from rainfall or irrigation (Roberts and Clanton 1992). The reduction of runoff from agricultural lands makes more water available for plant use, reduces soil erosion and reduces nutrient escape to the receiving surface water bodies. Boyle *et al.* (1989) proposed that the maintenance of adequate water infiltration depends on organic inputs. Organic amendments improve soil structure through the production of stable aggregates and macropores; this leads to higher infiltration rates. Aggregation may not be the only mechanism for increasing infiltration rates. Bouwer (1986) proposed that because of the large number of determinants influencing infiltration, no single factor could serve as an index for predicting the infiltration behavior of a particular soil. Research conducted by Boyle *et al.* (1989) indicated that increased infiltration rates measured after the first yearly addition of an organic amendment correlated with increased aggregate stability, while infiltration rates after the second and third year of organic amendments correlated more with decreased bulk density.

Multiple linear regression analyses of relationships between cumulative infiltration and physiochemical properties of soils indicated that a decrease in bulk density and an increase in aggregate stability are the major factors affecting infiltration rates (Boyle *et al.* 1989).

Roberts and Clanton (1992) suggested that infiltration rates are affected by the alteration of soil surface properties. Surface seals formed by the impact of raindrops often reduce infiltration rates of soils. The surface layer has higher bulk density and lower porosity than underlying soil. A laboratory experiment found that a surface seal formed on soils that did not receive manure treatment, while the application and incorporation of livestock manure prevented the formation of a surface seal. As a result, infiltration rates were higher in soils receiving livestock waste, and runoff volumes were generally less. Meek *et al.* (1982) also suggested that infiltration rates increased with manure applications due to alterations of the soil surface layer. They found that the application of manure greatly increased infiltration rates when measured during the cropping season, but little effect was found between cropping seasons. They suggested that the restricting layer for infiltration during the growing season is the soil surface, this being the zone that is altered by the application of manure. Between crops, the restricting layer would be deeper than 22.5 cm, because the disking operation would reduce the bulk density of the surface soil.

Throughout Alberta, many research sites are set up to study the effects of manure on soils and plant growth. The purpose of the study reported here was two-fold: to examine the effects of beef cattle manure application on soil physical properties and corresponding changes in the rate of infiltration, and to develop statistical models relating changes in soil physical properties to soil texture and net increase in soil organic matter content. Data acquired in this study will make a positive contribution for the establishment of manure loading capacity of soils.

2.2. Materials and Methods

2.2.1 Site Descriptions

The St. Vincent site (est. 1998) is 0.4 ha, located 1.6 km east of St. Vincent, AB, approximately 160 km northeast of Edmonton. The land is located on an east-facing slope with a relatively uniform 5% slope across the entire site. Soil conditions on the St. Vincent site vary with slope position. The soil belongs to the Lacorey soil series and is an Orthic Gray Luvisol. The Ap horizon is a loam consisting of 48/37/15% sand/silt/clay, while the underlying Bt_1 is a fine sandy loam with 59/21/19% sand/silt/clay. It is a well drained soil developed on a moderately fine till. There is no strong evidence of Ah or Ae horizons in this soil because of the mechanical mixing by cultivation. The thickness of the B horizon and depth to underlying C horizons varies with slope position. In the lower slope position, the soil profile is more characteristic of the Fergy soil series, which is an Eluviated Black Chernozem, developed on similar parent material to the Lacorey series.

The site layout consists of a randomized complete block design with four replicates. Treatment consisted of 40 Mg/ha/yr cattle manure applied in spring. The control plot received no manure and barley has been grown on all plots annually since establishment of the site.

The Lethbridge site (est. 1973) is located at the Agriculture and Agri-food Canada Lethbridge Research Center (Sommerfeldt and Chang 1985). The soil type is a calcareous Orthic Dark Brown Chernozemic clay loam soil consisting of 28/42/30% sand/silt/clay, on a relatively flat area. Cattle manure is applied to the site at 0, 30, 60, and 90 Mg/ha/yr and incorporated with a cultivator. Manure treatments are in a randomized complete block design with five replicate plots that have received manure since 1973. Barley was grown on the site from 1974 – 1995, canola in 1996, corn in 1997, triticale in 1998 and 1999, and barley again in 2000 – 2002.

The Breton Classical Plots (est. 1930) are located 3 km southeast of Breton, AB (Department of Soil Science, University of Alberta 1993). The soil on the site is an Orthic Gray Luvisol mapped as a Breton loam series. The soil texture is silty loam containing 33/55/12% sand/silt/clay. The site layout consists of strips subjected to the following treatments: cattle manure applied every fifth year, NPKS, NS, lime, lime + P, P, and manure + NPKS; there were two cropping rotations within each treatment (a five year rotation: wheat–oat–barley–legume–legume, and a two year rotation: wheat - fallow). Manure is added every fifth year in sufficient amounts to meet nutrient requirements of the crop, approximately 9 Mg/ha/year. The control was untreated soil. Soil measurements were conducted on the control, manure, and NPKS treatments, with the plots currently in oats and hay of the five-year rotation and wheat of the wheat fallow rotation, after harvest in the fall of 2001. The oat and fallow plots were cultivated during the fall after measurements had been conducted. Spring measurements were completed before spring cultivation or seeding.

2.2.2 Experimental Methods

Infiltration measurements were conducted using a single ring infiltrometer (Bouwer 1986). A steel ring, 30 cm in diameter, was pressed into the soil to a 10 cm depth. Care was taken to ensure that the ring went in straight and did not form cracks between ring and soil. Water was supplied using a Marriott tube and a constant ponding depth of 5 cm was maintained throughout the infiltration run. Water level in the Marriott tube was recorded in approximately 1-5 min intervals depending on the rate of water drop in the reservoir. Infiltration measurements ran for 1 hour, during which cumulative infiltration as a function of time was determined. Measurements were taken in the fall 2001 on all three sites and again in the spring 2002 on the Breton and St. Vincent sites. Soil water content was determined prior to infiltration measurements using TDR (Soil Moisture Equip. Corp.) to a depth of 10 cm just outside the ring.

Bulk density samples were taken in the fall 2001 for all sites at 0-10 cm and 10-20 cm depth intervals using a soil core sampler (Hoskin Scientific). Five cores, 10 cm deep with diameters of 5.5 cm, were taken randomly from each plot and dried at 105°C to a constant weight.

Organic matter content was determined using the wet oxidation method (Walkley and Black 1934). Samples were collected in the fall 2001 from all sites by taking composite samples from 5 locations in each plot at the 0-10 cm and 10-20 cm depth intervals with a shovel. Organic matter content was determined in duplicate on each sample collected.

Soil water retention was determined on samples collected in the spring 2002 using sieved, repacked samples collected at 0-10 cm and 10-20 cm depth intervals. Soil was passed through a 2 mm sieve, oven dried, then packed into rings 3 cm deep, 5.5 cm diameter, using a hydraulic press. Sufficient amounts of soil were added to the rings to match the field bulk density. Soil cores were placed on pressure plates and allowed to saturate for 5 days. Pressure was then applied until water stopped dripping from the exit port, at field capacity (33 kPa) and permanent wilting point (1500 kPa). Soil cores were dried at 105°C to a constant weight and water content was determined.

Wet aggregate stability was determined as described by Kemper and Rosenau (1986). Soil samples were collected from the field at 0-10 cm and 10-20 cm depth intervals in May 2002, approximately one month after snowmelt, and stored at 4°C. Five grams of 3-4 mm air-dried aggregates were placed on a 1.18 mm sieve. The sieves were placed on a wetted cotton pad to allow aggregates to wet by capillarity for 10 minutes. Sieves were then placed in the aggregate shaker and raised and lowered into pre-weighed aluminum cylinders containing distilled water, with a stroke length of 1.3 cm at 35 strokes/min for 3 minutes. The particles that fell through the sieves during the initial 3 min were considered to be unstable aggregates. Particles remaining on the sieve were water stable aggregates and other particles such as rocks. After the first 3 minutes, the aluminum cylinders containing distilled water were replaced with another pre-weighed set containing 2 g sodium hexametaphosphate (NaHMP)/L. Sieves were raised and lowered in this solution until no aggregates remained on the sieve, remaining particles being rocks and other insoluble debris. Cylinders were then oven dried until all water had evaporated, then weighed. The fraction of stable aggregate was calculated by:

$$\text{Stable Fraction} = \frac{\text{Mass (Soil in NaHMP)g}}{\text{Mass (Soil in H2O)g} + \text{Mass (Soil in NaHMP)g}}$$

2.2.3 Statistical analysis

Statistical analysis was performed using SAS (SAS Institute 1989). Analysis of variance was performed using the General Linear Model (proc GLM). Arithmetic means and standard errors are reported. The Student Newman Keuls (SNK) test with $P \leq 0.05$ was used to determine the significance of the differences among the main treatment effects. If there were other factors in the experiment (e.g., depth, year) besides manure application rate, the data were analyzed separately for each condition. Since the Breton plots are contained in strips, and not randomized, statistical analyses was performed using t-Tests (Proc ttest) with comparisons made between manure-NPKS, manure-control, and NPKS-control. Regression analysis was performed using the stepwise procedure (Proc Stepwise) where the independent variable was retained if $P \leq 0.15$.

2-3. Results

2.3.1 St. Vincent

Cumulative 1 hr infiltration measurements from spring 2001 and fall 2002 are presented in table 2-1. Mean 1 hr cumulative infiltration on the control plot were 12.1 cm for the fall measurement and 6.3 cm in the spring. The plot that received 40 Mg/ha/yr cattle manure was not significantly different from the control with values of 13.4 cm in the fall and 7.2 cm in the spring. Cultivation was not performed between the fall and spring measurements, and the development of a slight surface crust between fall and spring measurements was noticed. Moisture contents in the spring were also much higher than in fall, with volumetric soil moisture of approximately

10-15% in fall and 20-25% in spring. Cumulative infiltration in the spring was 48% lower than in the fall for the control and manured plots.

Bulk density measured in the fall 2001 was not significantly different between the two treatments at the 0-10 cm or 10-20 cm depth intervals (Table 2-2). Bulk density for the 0-10 cm depth interval was 1.23 Mg/m^3 for the control, and 1.27 Mg/m^3 in the manured plot. At the 10-20 cm depth interval, bulk density was 1.32 Mg/m^3 and 1.28 Mg/m^3 for control and manured plots, respectively.

Soil organic matter content measurements in fall 2001 were not significantly different. An organic matter content of 4.0% was found for both control and manured plots at the 0-10 cm depth interval, and 4.5% and 4.0% for control and 40 Mg/ha treatments respectively, for the 10-20 cm depth interval (Table 2-2).

Aggregate stability was determined on samples collected in spring 2002. No significant difference in the percentage of water stable aggregates was found between treated and control samples (Table 2-2). At the 0-10 cm depth interval, values were 25.5 and 21.9% for control and manured plots repectively. Values at the 10-20 cm depth interval were 34.4% for the control and 31.7% for manure treated plots (Table 2-2).

Values for field capacity (33 kPa) and permanent wilting point (1500 kPa) measured on disturbed samples from the two treatments were not significantly different (Table 2-3). Field capacity was 29.8 and 30.3% (v/v) for the 0-10 cm depth interval and 28.3 and 29.3% for the 10-20 cm depth interval for control and manured soils respectively. Permanent wilting points were 12.6 and 13.0% in the 0-10 cm depth interval and 12.6 and 12.8% in the 10-20 cm depth interval for control and manured soils, respectively.

2.3.2 Lethbridge

The rate of manure application had a significant effect on cumulative infiltration over a 1-hr period (Table 2-1). Infiltration rates were similar between the 0 and 30 and between the 60 and 90 Mg/ha/yr application rates, but there was a significant difference in infiltration between the 30 and 60 Mg/ha/yr application rates. Mean 1-hr cumulative infiltration ranged from 10.9 cm for the control to 22.6 cm for the 90 Mg/ha/yr treated soil. Cumulative infiltration rates for 60 and 90 Mg/ha/yr treatments were higher than the control by 97% and 106% respectively.

Bulk density measured in the fall 2001 was lowered by increasing rates of manure application (Table 2-2). Soil bulk densities were similar when treated with manure at rates of 0 and 30 Mg/ha/yr, but significant differences were observed among the 30, 60 and 90 Mg/ha/yr rates for the 0-10 cm depth interval. For the depth interval of 10-20 cm, only the 90 Mg/ha/yr rate produced a significantly lowered bulk density compared to the control.

Percent organic matter content increased significantly at all rates of manure application for the depth interval of 0-10 cm. A net increase of 1.5, 3.9 and 5.9% over the control was determined for the 30, 60 and 90 Mg/ha/yr treatments respectively (Table 2-2). A significant positive correlation between soil organic matter content and rate of manure application ($R^2 = 0.98$) was observed at this depth. At the 10-20 cm depth interval, the organic matter content was significantly higher than the control for the 60 and 90 Mg/ha/yr rate, but organic content was similar between 0 and 30, and between 60 and 90 Mg/ha/yr rates.

The percentage of water stable aggregates is shown in Table 2-2. Results were highly variable but significant differences between treatments were not found. Values were higher for the 60 and 90 Mg/ha/yr treatments for the 0-10 cm and 10-20 cm depth intervals, although the differences were not statistically significant. It was observed that the samples from the 60 and 90 Mg/ha/yr treatments contained flakes of manure that often outnumbered soil aggregates. This would have reduced the amount of aggregates in the sample and may have led to misleading results.

Field capacity (33 kPa) and permanent wilting point (1500 kPa) for the 0-10 cm depth interval were significantly affected by the rate of manure applied (Table 2-3). Field capacity was 37.0% (v/v) for the control and increased to 45.7% for the 90 Mg/ha/yr treatment. At permanent wilting point, volumetric water content also significantly increased from 20.7% for the control to 32.7% for the 90 Mg/ha/yr treatments. For the depth interval of 10-20 cm, significant differences were not found for field capacity or permanent wilting point.

2.3.3 Breton

Cumulative 1-hr infiltration was generally higher on plots receiving manure than on NPKS treatment or control, although significant differences were not always found (Table 2-1). The largest differences in infiltration were found between manure treated and control soil. Infiltration was significantly higher after manure treatment for most crops in the rotation, in both spring and fall. The exception was oats in the fall of 2001, where no significant differences were found between any of the treatments. There was an obvious trend to higher infiltration in manured soil but variability was high and more measurements may have been required to determine statistical differences between treatments.

Soil organic matter content for the 0-10 cm depth interval was highest for plots receiving manure and lowest for the control (Table 2-2). Organic matter content was 3-4% for the manured soil and 1-2% for the control.

For the 0-10 cm depth interval, bulk density was non-significantly lower on manured soil (Table 2-2). For the 10-20 cm depth interval, the bulk density of the manured plot was significantly lower than that of the control for oats and wheat crops only. Overall, changes of bulk density in the treated soils were small, and a larger number of samples may have been required to find significant differences.

The percentage of water stable aggregates was highest for manured soil, and lowest for control soil (Table 2-2). Hay of the five-year rotation produced the highest proportion of stable aggregates, up to 70%, while the wheat crop of the two-year rotation produced the lowest, approximately 20% in both treated and control plots. A composite sample from each plot was analyzed and hence statistical interpretation was not possible, but trends between treatments were visible.

Field capacity (33 kPa) and permanent wilting point (1500 kPa) were generally higher for the manure treated soil than for NPKS treated soil and control at the 0-10 cm and 10-20 cm depth intervals (Table 2-3). However, differences between treatments were small and, because one composite sample per treatment was measured, statistical analysis was not conducted.

2.4 Discussion

2.4.1 St.Vincent

The addition of cattle manure at 40 Mg/ha for three consecutive years had no significant effect on soil cumulative infiltration in either fall or spring.

While manure has been found to have a positive effect on infiltration in many soils, such as on the Lethbridge site, other researchers have also found that manure had no significant effect on infiltration (Sommerfeldt and Chang 1986; Miller 1999). In addition, applied manure did not affect any of the soil properties studied (bulk density, organic matter, aggregate stability, field capacity and wilting point) for depth intervals of 0-10 cm and 10-20 cm.

At the time of sampling and measurement, very little visible manure remained from the previous application. Rapid degradation of manure during the spring and summer months following application may have limited its effects on soil physical properties. Mathers and Stewart (1970) found that under well-aerated conditions in the laboratory, almost 50% of added manure organic carbon evolved as CO_2 in 90 days. Darwish *et al.* (1995) reported that rapid microbial degradation of manure was apparently responsible for the lack of marked changes in soil physical properties on sandy loam, silt loam, and clay loam soils that received a total of 289 Mg/ha of dry weight manure over 15 years.

The absence of effects on either the physical condition of the soil or infiltration may be due to the relatively low rate of manure application and the short duration of the study (3 years). At the Lethbridge site, even after manure had been applied at 30 Mg/ha for 30 consecutive years, the changes were small and often not significant. It was primarily at the higher rates (60 and 90 Mg/ha) where significant differences were found. Unger and Stewart (1974) reported that when feedlot manure was applied annually for four years, at rates adequate to supply nutrient requirements of plants, no statistically significant effects on soil physical properties were found. Effects on soil physical properties were significant only at higher rates of manure application.

2.4.2 Lethbridge

Long-term application of beef cattle feedlot manure increased soil water infiltration (Table 2-1).This is consistent with other studies (Mathers *et al.* 1977; Martens and Frankenberger 1992; Miller *et al.* 2002,). The soil property that shows the strongest correlation with increased infiltration appears to be the decreased bulk density ($R^2 = 0.97$) in the top 10 cm of the soil.

The decrease in bulk density can be accounted for by two factors. First, the addition of manure increases the organic matter content of the soil, leading to an increase in aggregation and aggregate stability (Chaney and Swift 1984). Second, the decrease in bulk density could be the result of a dilution effect when added organic matter is mixed with the denser mineral fraction of the soil (Powers *et al.* 1975). On this particular site, it is more likely that the dilution effect is primarily responsible for the decreased bulk densities, as there were no significant differences or trends in aggregate stability between the manure treatments. This is contrary to other studies (Cross and Fischbach 1973; Unger and Stewart 1974; Mazurak *et al.* 1977; Aoyama *et al.* 1999). The lack of change in aggregate stability may have been due to methodology. Our measurements were taken with 1 mm sieves, while other studies used 250 μm sieves. The presence of large amounts of partially decomposed manure in samples of the 60 and 90 Mg/ha/yr treatments may have also limited the amount of mineral aggregates detected.

Soil organic matter content for the 0-10 cm depth interval was found to increase linearly with an increase in manure application rate, according to $y=0.059x+3.66$ ($R^2=0.98$), where y is the percent increase in soil organic matter content and x is the rate of application in Mg/ha/yr. This is consistent with results of other studies that found a linear increase in organic matter content with increasing rates of manure application (Meek *et al.* 1982; Sommerfeldt and Chang 1985).

While a strong correlation ($R^2=0.98$) is found between cumulative infiltration and organic matter content, the increase in organic matter content alone does not explain the increased infiltration. It has been found by others (Tiarks and Mazurak 1974; Unger and Stewart 1974) that as organic matter content increases, the stability and geometric mean diameters of soil aggregates also increase. Significant changes in aggregate stability could not be found in this study, indicating that changes in bulk density were primarily responsible for increased infiltration.

The decrease in bulk density appeared to account for increased infiltration. However, changes to the surface properties of the soil should not be ignored. The surface layer can impede water infiltration if a soil crust forms. The addition of manure has been shown to prevent the formation of surface seal (Roberts and Clanton 1992). While no attempt was made in this study to measure the soil crust, a slight crust was observed on the 0 and 30 Mg/ha/yr treatments. The 60 and 90 Mg/ha/yr treatments contained no evidence of crusting, and there was a visible layer of manure on the soil surface.

Field capacity and permanent wilting point were both increased by the addition of manure. Other researchers (Unger and Stewart 1974; Miller 1999) have also found increases in field capacity and in permanent wilting point with manure applications. Water held in the soil is controlled by the volume and size of soil pores, and by the surface area of the soil (Khaleel *et al.* 1981). At water potentials near field capacity, water content increases as a result of an increased number of small pores. The addition of organic material to soils will increase the surface area and lead to greater water retention at lower water potentials, e.g., at permanent wilting point.

The application of manure had a positive effect on soil physical properties and water infiltration. The largest differences in infiltration were found for the 60 and 90 Mg/ha/yr treatments compared to the control. Bulk density decreased as the rate of manure application increased, due to dilution with partially decomposed manure, leading to higher organic matter content. Water retention was significantly affected by the rate of manure application. It should be noted that the greatest change in soil properties compared to control occurred at the 60 Mg/ha/yr rate of manure application. Very small, or no differences in soil properties were found between the 0 and 30 Mg/ha/yr rate. Little difference was found between the 60 and 90 Mg/ha/yr treatments. Rapid degradation of applied manure at 30 Mg/ha/yr perhaps did not allow for significant accumulation of manure and soil organic matter content. At 60 Mg/ha/yr, manure does not fully decompose, allowing for an annual accumulation of manure and degraded manure products. This could be seen at the time measurements were taken. Very little manure remained in the 30 Mg/ha treatment, but manure was visible and abundant on the 60 and 90 Mg/ha treated soils, on the surface and in the soil samples collected.

2.4.3 Breton

Low rates of beef cattle manure application over seventy five years have increased cumulative infiltration on the Breton site. Although the amount of increase was not significant for all crops, the manure treated plots on average had higher infiltration than NPKS treated or control soils. Infiltration rate depends upon the proportion of larger pores, stability of soil aggregates, soil water content and surface soil conditions (Sweeten and Mathers 1985). On the Breton site, manure treated soil had a lower bulk density, higher amounts of water stable aggregates, and slight increases in field capacity and permanent wilting point. While differences between the manured and control soils were not always statistically significant, a trend could be seen. Because the changes occurring were small and the tests were of low sensitivity, more samples would possibly produce statistically different results.

Changes in soil physical properties were apparent, although small. The addition of manure every fifth year at a rate sufficient to meet the nutrient requirements of crops does not allow for rapid or drastic changes to occur in soil physical properties. Rapid degradation of manure prevents large increases in organic matter content and therefore limits the extent of changes to soil physical properties. If manure were applied at this rate over a short time period, it would be expected that no change in cumulative infiltration or physical properties would be found. However, due to the extended length of application (75 years), slight increases in soil physical properties have occurred and the quality of the soil has been maintained and/or improved.

The wheat/fallow rotation showed the greatest effect of organic amendment. Untreated soil in this rotation contains a lower level of organic matter (about 1%) than any of the treated soils. It is characterized as having low infiltration rates, high bulk density and a low percentage of water stable aggregates compared to fertilized soils (Tables 2-1, 2-2). The effects of low organic matter content on infiltration and on soil physical condition are clearly visible. Harris *et al.* (1966) found that soil aggregate stability rapidly decreases when soils are monocropped with annuals that supply little residue to replenish the soil organic matter reserves. The decreased aggregate stability allows for slaking and clogging of soil pores during infiltration, and leads to low infiltration rates. The addition of manure to this cropping system led to increased soil quality, but not to the same quality that was found in the hay and oats crop of the five-year rotation.

Overall, manure had a positive effect in maintaining the quality of the soil on the Breton site. The addition of manure at low rates was effective in increasing infiltration and aggregate stability, and in lowering bulk densities. The low rate of manure applied does not allow for a large increase in soil quality, based on these parameters, but a positive effect of applied manure was found. If the manure did not play a role in increasing the quality of the soil, it did prevent significant degradation of soil quality over the last 75 years of cropping.

2.4.4 Predicting changes to soil properties using regression equations.

Information regarding soil organic matter and soil physical properties was found on three sites receiving cattle manure as an organic amendment. The sites differed in rates and duration of manure application, as well as in soil texture and climatic conditions. The primary effect of manure was an increase in soil organic matter content. Organic matter content is dependent on factors such as the rate and duration of manure application and soil texture (Sommerfeldt and Chang 1988; Darwish *et al.* 1995). Manure application also changes the physical properties of soil (Unger and Stewart 1974; Sommerfeldt and Chang 1984; Martens and Frankenberger 1992).

The three sites studied were highly diverse in both rate and duration of manure applications, and in soil texture. Multiple regression analysis indicated that the increase in soil organic matter content is a function of the rate and duration of manure application, and of soil texture (Table 2-4). A strong correlation was found with an R^2 value of 0.97. Organic matter content is affected more by the rate of manure application than by the duration of application. This is consistent with studies by Sommerfeldt and Chang (1988) who found that soil organic matter accumulated faster with higher levels of manure application, than with number of years of application. The most rapid decomposition of the applied organic matter occurred within the first year after application and varied with the level of application (Sommerfeldt and Chang 1988). If the decomposition of manure follows the decay series presented by Pratt *et al.* (1973), manure decomposition is highest in the first year and approaches zero over time. An assumption commonly made in soil organic carbon models is that the decomposition of organic matter in one year is not affected by manure applied before or after. Given this, higher rates of manure applied will result in greater amounts of manure remaining in the soil at the end of each year, leading to higher levels of organic matter accumulation. Thus, applying manure to the soil for longer durations will increase soil organic matter, but to a lesser degree. If the highest rate of decomposition is in the first year, and successive decay occurs in the 2nd, 3rd...n years, little organic matter from the earliest applications will remain as time goes on. Because of this, the largest accumulation of soil organic matter will occur in the first year, and will be largely influenced by the rate of manure applied.

Bulk density data for the three sites were used to develop linear regression equations among soil organic content, soil texture and percent reduction in bulk density in the top 10 cm (Table 2-4). Percent reduction in bulk density over the control was used to compensate for the large differences in the soil properties from the three sites. A significant linear relationship was found, $R^2 = 0.93$, where percent decrease in bulk density is a function of net increase in soil organic matter content and the percent clay content of the soil. Khaleel *et al.* (1981) took data from 12 sources that reported changes in soil organic matter content and bulk density as a result of organic waste applications ranging from 1 – 85 years, and found a linear regression equation (Table 2-5). The equation, developed from 42 observations shows a linear relationship based solely on net increases in organic C over the control. For the three soils from our study, the derived regression equation includes clay content as a variable, which gives a stronger correlation than does the regression equation found by Khaleel *et al.* (1981).

Regression equations expressing changes in field capacity and permanent wilting point are shown in Table 2-4. Percent increases in field capacity were directly linked to the decreased bulk density, although only a weak correlation was found ($R^2 = 0.64$). On the other hand, percent changes in wilting point were found to be more highly dependent on changes in soil organic matter content ($R^2 = 0.81$). Water retention at higher matric potentials, such as those at field capacity, is dependent on the volume of soil pores; thus, soil pore volume and porosity are affected by decreasing soil bulk density. At lower matric potentials, e.g., wilting point, nearly all pores are filled with air and the moisture content is controlled primarily by the surface area and the thickness of water films on these surfaces (Khaleel *et al.* 1981). With a decrease in soil bulk density, there is a corresponding increase in soil porosity; thus, a relationship between an increase in field capacity and a decreased bulk density is reasonable. At wilting point the increased organic matter content of the soil as a result of manure addition leads to greater surface area and therefore an increase in water retention.

Sandy soils have low specific surface area and large pores, resulting in low water holding capacities, while soils high in clay have large specific surface areas and higher porosities, and are characterized as generally having higher water holding capacities. Khaleel *et al.* (1981) found that percent increases of field capacity and permanent wilting point can be expressed by an exponential regression equation, with net increase in organic matter content and percent sand content as independent variables (Table 2-5). Data from Khaleel *et al* (1981) and the data from our study are used in the regression equations for field capacity and wilting point of Khaleel *et al* (1981) (Figure 2-1 and 2-2). The percent increases in field capacity and wilting point closely fit the exponential regression with the exception of one outlying data point (Figure 2-1 and 2-2). This point is found to have a high net increase in organic matter content (5.7%) over the control. The exponential regression equation from Khaleel *et al.* (1981) is only valid for net changes in organic matter content < 2.6%. With further net changes in organic matter content, the equation predicts decreases in relative field capacity and wilting point (Figure 2-3).

Predicting increases in field capacity and wilting point using either of the regression equations may result in significant errors. The linear regression for predicting field capacity in this study does not give a high R^2 value and more soils should be tested. The equation by Khaleel *et al.* (1981) has a higher R^2 value but is only valid when dealing with a small increase in organic matter content, $< 2.6\%$. For permanent witling point, both models gave similar R^2 values; again, the regression by Khaleel *et al.* (1981) is valid for absolute net increases in soil organic matter content less than 2.6%.

If field capacity and wilting point increase equally, there will not be an increase in plant available water holding capacity. Furthermore, if water content at wilting point increases more than field capacity, the plant available water holding capacity can decrease with the application of manure. For example, consider a soil (30% clay) from the Lethbridge site with an initial bulk density of 1.2 Mg/m^3 and an absolute net increase in organic matter content of 4% due to manure application. Using the regression equations of this study, bulk density would decrease by 18% relative to the original soil. If field capacity of the soil is initially 37%, it would increase to 42.7%, an absolute increase of 5.7%. The wilting point, initially at 20%, increases to 29%, an absolute gain of 9%. The increase in field capacity is less than the increase in wilting point and the plant available water holding capacity is reduced by 3.3%. Another example: a soil from the Breton site containing 12% clay with a bulk density of 1.28 Mg/m^3 shows an increase in net organic matter content of 1.7%. The bulk density decreases by 12% to 1.13 Mg/m^3. Field capacity, originally at 25%, increases to 27.7%, a net increase of 2.7%. Wilting point, originally at 15%, increases to 17.7%, also an increase of 2.7%. Increases in field capacity and wilting point are equal and there is no change in plant available water holding capacity. These results indicate that although manure application improves the general physical condition of soils, it does not necessarily improve plant available water holding capacity; it may even decrease it in some cases. This is contrary to a study by Hudson (1994). Using published data for soils that covered a wide range of organic matter contents in three soil texture classes - sand, silt loam, and silty clay loam, he found a significant positive correlation between soil organic matter content and estimated plant available water holding capacity in all three textural groups ($R^2 = 0.73$, 0.42 and 0.67 for sand, silt loam, and silty clay loam respectively). As organic matter increased, the volume of water held by the soil at field capacity increased much more rapidly than the volume of water held at wilting point, resulting in an increase in available water holding capacity (Hudson 1994). Soil organic matter levels in the soils selected by Hudson were due to variations in native organic matter for soils of similar texture. The soils in our study varied in organic matter content due to accumulations from different rates and durations of cattle manure applications. Hudson (1994) claimed that many studies failed to demonstrate a relationship between organic matter content and available water holding capacity because they were not properly designed to do so, and effects of organic matter levels on available water holding capacity were masked by excessive variations in soil texture. This may have been the case in other studies, but texture on the three sites of this study was constant among the treatments, and available water holding capacity was found to be either unaffected or decreased. It is possible that soil organic matter derived from manure does not behave the same as "native" organic matter in its effect on soil structure and the corresponding change in plant available water holding capacity. The "native" organic matter of soil is derived over long time periods, from the decomposition of plant products and other natural processes, and may influence these factors differently.

An attempt was made to describe changes in cumulative infiltration as a function of a net soil organic matter increase, but a significant relationship could not be found with the data from this study.

2.5 Conclusion

A net increase in soil organic matter content derived from cattle manure application is a function of the rate and duration of manure application, and soil texture. The analysis of the data has also shown that changes to soil physical properties such as bulk density, field capacity and wilting point can be related to net increases in soil organic matter content. These relationships can be useful in predicting changes in physical properties of soils when manure is applied, although extrapolation beyond the conditions tested may result in significant errors. This was shown with the equations relating increases in field capacity and permanent wilting point due to a net soil organic matter increase (Khaleel *et al.* 1981). Relationships found in this study are comparable with those of Kheleel *et al.*, but significantly extend the range of applicability. The addition of manure and the corresponding accumulation of soil organic matter have little or negative effect on the plant available water holding capacity of soil, if the increase in wilting point is more than the increase in field capacity.

Table 2-1: Summary of 1hr cumulative infiltration (cm) measured on 3 sites in the Fall 2001 and Spring 2002.

	Cumulative Infiltration (1 hr)	
	Fall 2001	Spring 2002
St. Vincent		
0 Mg/ha	12.1 ± 1.0 [†] a	6.3 ± 2.0 a
40 Mg/ha	13.4 ± 2.0 a	7.2 ± 1.2 a
Lethbridge		
0 Mg/ha	10.9 ± 0.7 b	
30 Mg/ha	14.0 ± 1.0 b	
60 Mg/ha	21.5 ± 2.5 a	
90 Mg/ha	22.6 ± 2.6 a	
Breton		
Oats - 5 year rotation		
Manure	13.6 ± 2.8 a	18.3 ± 0.9 a
NPKS	8.0 ± 2.7 a	13.1 ± 1.8 b
Control	7.3 ± 2.2 a	14.4 ± 1.8 b
Hay - 5 year rotation		
Manure	11.1 ± 0.9 a	28.3 ± 2.7 a
NPKS	10.3 ± 0.3 a	10.9 ± 2.9 b
Control	4.1 ± 0.6 b	14.7 ± 1.4 b
Wheat - 2 year rotation		
Manure	11.1 ± 3.9 a	9.1 ± 1.4 a
NPKS	4.3 ± 0.9 b	2.5 ± 0.3 b
Control	2.9 ± 0.3 b	1.1 ± 0.2 c

[†] Arithmetic means ± standard errors followed by lowercase letters indicating statistical difference ($P \leq 0.05$). Those followed by the same lowercase letter within each season are not significantly different.

Table 2-2: Summary of bulk density, organic matter and percent water stable aggregates measured on 3 sites for 0-10 cm and 10-20 cm depth intervals.

	Bulk Density		Organic Matter		WSA	
	0-10 cm	10-20 cm	0-10 cm	10-20 cm	0-10 cm	10-20 cm
	---------------Mg/m^3-------------		---------------%---------------		---------------%---------------	
Lethbridge						
0 Mg/ha	1.22 ± 0.01[†] a	1.34 ± 0.02 a	3.7 ± 0.3 d	2.5 ± 0.2 b	10.4 ± 0.9 a	23.3 ± 3.0 a
30 Mg/ha	1.17 ± 0.04 a	1.32 ± 0.01 a	5.2 ± 0.3 c	3.2 ± 0.2 b	10.6 ± 1.5 a	23.2 ± 3.1 a
60 Mg/ha	1.01 ± 0.01 b	1.22 ± 0.06 a	7.6 ± 0.6 b	5.6 ± 0.6 a	14.1 ± 2.4 a	26.4 ± 2.6 a
90 Mg/ha	0.91 ± 0.04 c	1.11 ± 0.03 b	8.8 ± 0.3 a	5.8 ± 0.3 a	15.2 ± 1.2 a	26.5 ± 2.9 a
St. Vincent						
0 Mg/ha	1.23 ± 0.02 a	1.32 ± 0.03 a	4.0 ± 0.5 a	4.5 ± 0.8 a	25.5 ± 2.2 a	34.4 ± 3.2 a
40 Mg/ha	1.27 ± 0.03 a	1.28 ± 0.06 a	4.0 ± 0.9 a	4.0 ± 1.3 a	21.9 ± 0.7 a	31.7 ± 1.1 a
Breton						
Oats - 5 year rotation						
Manure	1.07 ± 0.06 a	1.19 ± 0.04 b	3.0	2.4	38.0	44.9
NPKS	1.18 ± 0.05 a	1.26 ± 0.04 ab	2.6	2.6	36.6	26.2
Control	1.28 ± 0.10 a	1.42 ± 0.06 a	1.7	1.5	31.6	22.0
Hay - 5 year rotation						
Manure	1.08 ± 0.05 a	1.12 ± 0.03 a	4.2	1.9	69.2	56.1
NPKS	1.18 ± 0.07 a	1.17 ± 0.05 a	2.9	1.8	47.3	44.3
Control	1.22 ± 0.05 a	1.25 ± 0.05 a	2.1	1.8	37.4	29.3
Wheat - 2 year rotation						
Manure	1.07 ± 0.06 a	1.25 ± 0.05 b	3.4	1.5	19.8	23.1
NPKS	1.18 ± 0.05 a	1.29 ± 0.05 b	1.4	0.7	15.0	20.1
Control	1.28 ± 0.10 a	1.46 ± 0.02 a	1.1	0.6	15.8	13.7

[†] Arithmetic means ± standard errors followed by different lowercase letters indicating statistical difference ($P \leq 0.05$). Those followed by the same lowercase letter within each depth interval are not significantly different. Numbers without letters following indicate that statistics were not possible.

Table 2-3: Water retention at field capacity (33 kPa) and permanent wilting point (1500 kPa) from soil for 0-10 cm and 10-20 cm depth intervals for 3 sites.

	Water Retention		Water Retention	
	0-10 cm		10-20 cm	
	33 kPa	1500 kPa	33 kPa	1500 kPa
	% (v/v)		% (v/v)	
Lethbridge				
0 Mg/ha/yr	37.0 ± 1.6[†]b	20.7 ± 0.8 b	29.2 ± 0.4 a	23.3 ± 0.6 a
30 Mg/ha/yr	39.7 ± 1.6 a	22.0 ± 0.8 b	29.6 ± 0.9 a	23.2 ± 1.4 a
60 Mg/ha/yr	40.6 ± 1.2 a	30.5 ± 1.3 a	31.8 ± 0.8 a	26.4 ± 1.2 a
90 Mg/ha/yr	45.7 ± 2.9 a	32.7 ± 2.2 a	32.6 ± 0.7 a	26.5 ± 1.0 a
St. Vincent				
0 Mg/ha/yr	29.8 ± 0.9 a	12.6 ± 0.3 a	28.3 ± 0.5 a	12.6 ± 0.6 a
40 Mg/ha/yr	30.3 ± 2.3 a	13.0 ± 0.7 a	29.3 ± 0.3 a	12.8 ± 0.7 a
Breton				
Oats - 5 year rotation				
Manure	29.3	18.1	27.2	19.5
NPKS	27.2	16.4	27.1	17.2
Control	24.1	15.1	25.2	17.2
Hay - 5 year rotation				
Manure	28.5	19.1	28.4	18.5
NPKS	28.4	18.2	27.2	17.2
Control	26.1	18.4	27.1	17.5
Wheat - 2 year rotation				
Manure	28.4	18.2	27.5	17.2
NPKS	28.1	15.1	25.4	16.3
Control	26.4	13.4	25.1	15.2

[†] Arithmetic means ± standard errors followed by different lowercase letters indicating statistical difference ($P \leq 0.05$). Those followed by the same lowercase letter within each depth interval are not significantly different. Numbers without letters following indicate that statistics were not possible.

Table 2-4: Regression equations for changes in soil physical properties as a result of cattle manure applications in the top 10 cm of the soil.

Property	Units	Equation	R^2	No. of Obs.
Organic Matter	%	$\Delta OM = 0.061(R) + 0.032(Dur) - 0.07(Sand) + 0.84$	0.97	7
Bulk Density	Mg/m^3	$\Delta BD = -6.51(\Delta OM) + 0.46(Clay) - 6.53$	0.93	7
Field Capacity	% v/v	$\Delta FC = -0.67(\Delta BD) + 2.86$	0.64	7
Wilting Point	% v/v	$\Delta WP = 12.016(\Delta OM) - 2.67$	0.81	7

ΔOM = Net increase in organic matter (%) over the control.
(Soil organic matter of manure treatment – soil organic matter of control).
(R) = application rate (Mg/ha/yr), (Dur) = duration of application (years).
ΔBD = Relative % increase in bulk density (BD).
(Manure-incorporated soil bulk density – control soil)/(control soil BD) × 100
ΔFC = Relative % increase in field capacity (FC)
(Manure-incorporated soil FC – control soil FC)/(control soil FC) × 100
ΔWP = Relative % increase in wilting point (WP).
(Manure-incorporated soil WP – control soil WP)/(control soil WP) × 100
Sand = % sand present in the soil.
Clay = % clay present in the soil.

Table 2-5: Regression equations for changes in soil physical properties as a result of waste applications (Khaleel *et al.* 1981).

Property	Units	Equation	R^2	No. of Obs.
Bulk Density	Mg/m^3	$\Delta BD = 3.99 + 6.62(\Delta C)$	0.69	42
Field Capacity	% v/v	$\Delta FC = \exp[1.09 + 2.14(\Delta C) - 0.41(\Delta C)^2 - 0.017(\text{Sand}) + 0.00038(\text{Sand})^2]$	0.81	21
Wilting Point	% v/v	$\Delta WP = \exp[1.12 + 2.25(\Delta C) - 0.44(\Delta C)^2 - 0.044(\text{Sand}) + 0.0007(\text{Sand})^2]$	0.79	19

ΔBD = (Waste-incorporated soil bulk density (BD)–control soil BD)/(control soil BD)×100
ΔC = (Waste-incorporated soil organic carbon (C)–control (without waste) soil organic C).
ΔFC = % increase in field capacity (FC)
(Waste-incorporated soil FC–control soil FC)/(control soil FC)×100.
ΔWP = % increase in wilting point (WP).
(Waste-incorporated soil WP–control soil WP)/(control soil WP)×100.
Sand = % sand present in the soil.
Clay = % clay present in the soil.

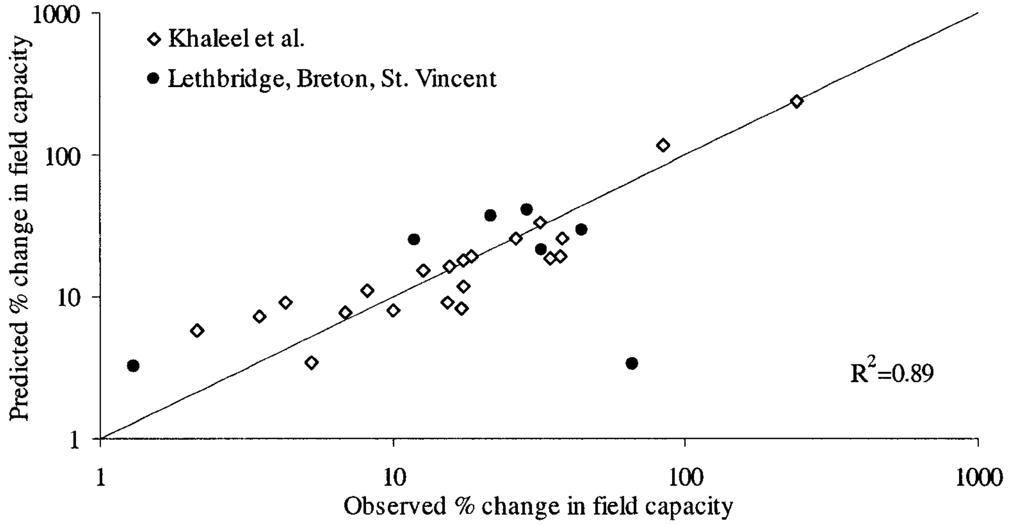


Figure 2-1: Observed and predicted changes in field capacity over the control using the regression equations from Khaleel *et al.* (1981). Note that the outlier has the highest change in soil organic matter = 5.7%.

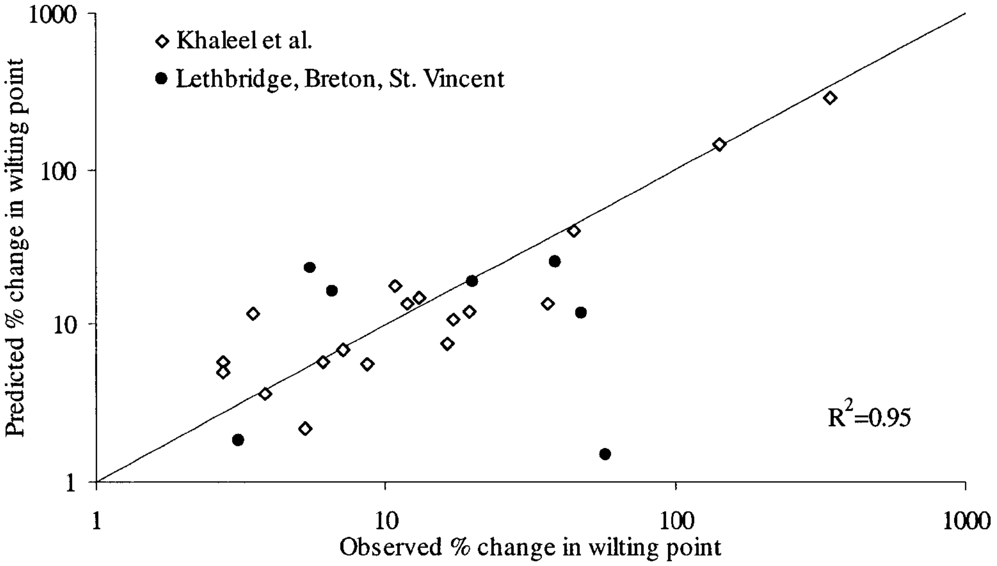


Figure 2-2: Observed changes in water content over the control at wilting point compared with predicted changes based on the regression equation from Khaleel *et al.* (1981). Note that the outlier has the highest change in soil organic matter = 5.7%.

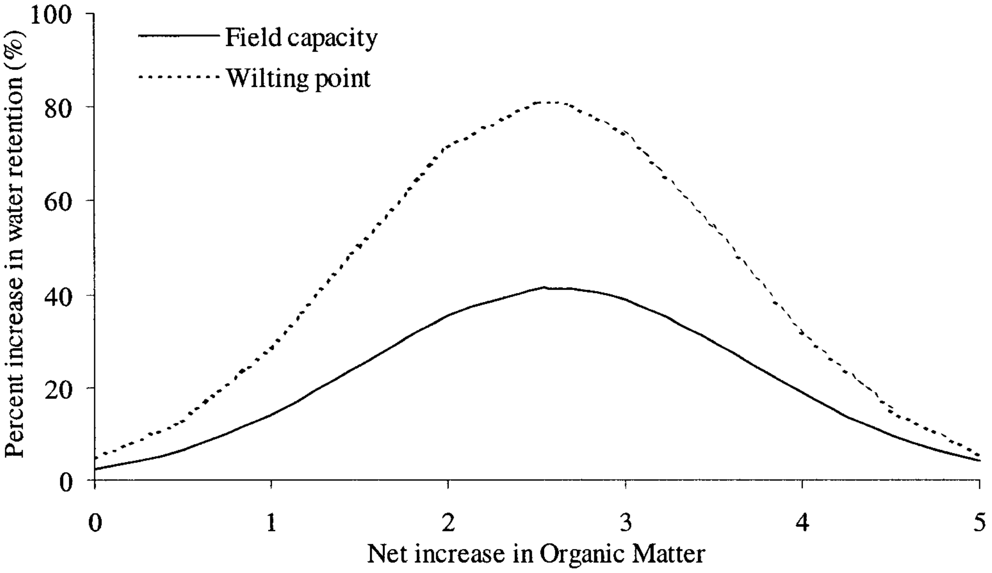


Figure 2-3: Percent increases in field capacity and wilting point as functions of a net increase in organic matter based on the exponential regression equation from Khaleel *et al.* (1981).

2.5 References

Aoyama, M., Angers, D.A., and N'dayegamiye, A. 1999. Particulate and mineral associated organic matter in water stable aggregates as affected by mineral fertilizer and manure applications. Can. J. Soil. Sci. 79:295-302.

Bouwer, H. 1986. Intake rate: Cylinder infiltrometer. Pages 825-844 *in* Methods of soil analysis, Part 1, 2nd ed. Agron. Monog. ASA and SSSA, Madison, WI. A. Klute (ed.).

Boyle, M., Frankenberger, W.T. Jr., and Stolzy L.H. 1989. The influence of organic matter on soil aggregation and water infiltration. J. Prod. Agric. 2:290-299.

Chaney, K., and Swift, R.S. 1984. Studies on aggregates stability. I. Reformation of soil aggregates. J. Soil Sci. 37:329-335.

Cross, O.E., and Fischbach, P.E. 1973. Water intake rates on silt loam soil with various manure applications. Trans. ASAE 16:160-163.

Darwish, O.H., Persaud, N., and Martens, D.C. 1995. Effect of long term application of animal manure on physical properties of three soils. Plant Soil 176:289-295.

Harris, R.F., Chesters, G., and Allen, O.N. 1966. Dynamics of soil aggregation. Adv. Agron. 18: 107-169.

Hillel, D. 1982. Introduction to soil physics. Academic Press. New York.

Hudson, D.B. 1994. Soil organic matter and available water capacity. J. Soil Water Cons. 49:189-194.

Khaleel, R., Reddy, K.R., and Overchash, M.R. 1981. Changes in soil physical properties due to organic waste applications: Review. J. Environ. Qual. 10:133-141.

Kemper, W.D., and Rosenau, R.C. 1986. Aggregate stability to water and size distribution. In Methods of Soil Analysis, Part I, Physical and Mineralogical Methods – Agronomy Monograph No. 9, 2nd ed.

Martens, D.A., and Frankenberger, W.T. Jr. 1992. Modification of infiltration rates in an organic amended irrigates soil. Agron. J. 84:707-717.

Mathers, A.C., Stewart, B.A., and Thomas, J.D. 1977. Manure effects on water intake and runoff quality from irrigated grain sorghum plots. Soil Sci. Soc. Amer. J. 41:782-785.

Mazurak, A.P., Chesin, L., and Thijeel, A. 1977. Effects of beef cattle manure on water stability of soil aggregates. Soil Sci. Soc. Amer. J. 41:613-615.

Meek, B., Graham, L., and Donovan T. 1982. Long term effects of manure on soil nitrogen, phosphorous, potassium, sodium, organic matter, and water infiltration. Soil Sci. Soc. Amer. J. 46:1014-1019.

Miller, J.J, Sweetland, N.J., and Chang, C. 1999. Impact on long-term manure applications on soil physical properties. Farming for the Future Research Program. Final technical report. Project 970793. Alberta Agriculture Research Institute.

Miller J.J., Sweetland, N.J., and Chang, C. 2002. Hydrological properties of a clay loam soil after long-term cattle manure application. J. Environ. Qual. 31:989-996.

Powers, W.L., Wallingford, G.W., and Murphy, L.S. 1975. Research status on effects of land application of animal wastes. EPA-660/2-75-010. USEPA, Washington, D.C.

Pratt, P.F., Broadbent, F.E., and Martin, J.P. 1973. Using organic wastes as nitrogen fertilizers. Calif. Agric. 27:10-13.

Roberts, W.D., and Clanton, C.J. 1992. Plugging effects from livestock waste application on infiltration and runoff. Trans. ASAE 35:515-522.

Sommerfeldt, T.G., and Chang, C. 1985. Changes in soil properties under annual applications of feedlot manure and different tillage practices. Soil Sci. Soc Amer. J. 49:983-987.

Sommerfeldt, T.G., and Chang, C. 1986. Soil water properties as affected by twelve annual applications of cattle feedlot manure. Soil Sci. Soc Amer. J. 51:7-9.

Sommerfeldt, T.G., Chang, C., and Entz, T. 1988. Long-term annual manure applications increase soil organic matter and nitrogen, and decrease carbon to nitrogen ratio. Soil Sci. Soc Amer. J. 52:1688-1672.

Sweeten, J.M., and Mathers, A.C. 1985. Improving soils with livestock manure. J. Soil Water Conserv. 40:206-210.

Tiarks, A.E., Mazurak, A.P., and Chesnin, L. 1974. Physical and chemical properties of soil associated with heavy applications of manure from cattle feedlots. Soil Sci. Soc. Amer. Proc. 38:826-830.

Unger, P.W., and Stewart, B.A. 1974. Feedlot waste effects on soil conditions and water evaporation. Soil Sci. Soc. Amer. Proc. 38:954-958.

Walkley, A., and Black, I.A. 1934. An examination of the Degtareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Sci. 37:29-39.

Chapter 3

A New Equation for Estimating Sorptivity and the Wetting Front Potential During Infiltration.

3.1 Introduction

Information regarding water infiltration into the soil is required for many watershed models that attempt to predict runoff, erosion, and water movement in soils. Because Richard's (1931) equation describing water movement in soils is highly non-linear, an exact analytical solution for infiltration of water in soils is difficult to obtain and apply (Philip 1957). Simple models have been developed that allow predictions of infiltration to be made utilizing parameters that can be evaluated from physical properties of the soil. Two popular models that have been used extensively are the Green and Ampt (1911) and Philip (1957a) equations. It can be shown that in both of these equations a "sorptivity" parameter appears (Kutilek and Nielson 1994). Sorptivity (S) is a function of the mean wetting front matric potential (H_f) and saturated (K_s)/unsaturated hydraulic conductivity (K) of the soil (Kutilek and Nielson 1994). While the wetting front potential has a physical basis, it is not easily measured, except by exacting, time-consuming procedures (Mein and Farrell 1974). Exact calculation of the "proper" H_f to be used in infiltration equations requires information on the functional relationship between water potential (h) and water content (θ) (i.e., soil water characteristics curve) and between hydraulic conductivity (K) and water content (θ) (i.e., relative permeability curve) (Philip 1957a). Approximate solutions to the infiltration problem require estimates of the mean wetting front water potential, H_f. Literature has given the greatest acceptance to estimating the wetting front potential using the hydraulic conductivity (K) - water potential (h) relationship (Bouwer 1964; Mein-Larson 1973; Neuman 1976). This relationship provides a reasonable estimate of H_f, but the K-θ relationships are not always available for a soil. The relationship can be theoretically estimated from the more easily measured soil water characteristic curve using models such as the van Genuchten (1980) equation, but determination of the soil water characteristic curve applicable for undisturbed field soil conditions is still time consuming and, while the model gives results that match experimental observations for many soils (e.g., van Genuchten 1980), significant errors can still arise (Yates *et al.* 1992).

Due to the difficulty in producing a reliable conductivity (K) - matric potential (h) relationship and the errors that can arise in using it to predict infiltration parameters, there is a need for an easier and quicker method for estimating H_f, and thus soil water infiltration. A new model is proposed (K_s model) that limits the input parameters to saturated hydraulic conductivity (K_s), and the initial (θ_i) and saturated water (θ_s) contents. This model allows an estimation of the average wetting front potential required for an infiltration model, while using a few easily attainable input parameters. This chapter evaluates the new model for a wide range of soils, and compares it to other models found in the literature (Bouwer 1964; Mein and Larson 1973; Neuman 1976).

3.1.1 Infiltration Models

Green and Ampt (1911) were among the first investigators to develop a model predicting the amount of infiltration into a vertical column of uniform porous media. This model assumes that the column of soil is homogeneous to a depth greater than the depth of water percolation, and that the soil may be viewed as a bundle of capillary tubes differing in area, shape and direction. Water movement in the soil is regarded as piston-like flow, where the soil is fully saturated to a depth the water has penetrated under ponded conditions, and below the zone of saturation is the soil at the initial water content.

The Green and Ampt model, which describes the rate of infiltration, is expressed by

$$i = \frac{b}{I} + K_S \qquad (1)$$

where i is the rate of infiltration (m/s), I is cumulative infiltration (m), K_s is the saturated hydraulic conductivity, and b is a parameter related to physical properties of the soil,

$$b = K_s H_f(\theta_s - \theta_i) \tag{2}$$

where H_f is the "average" matric potential difference across the wetting front, (i.e., the wetting front potential). The Green and Ampt equation models water moving in the soil as a saturated plug during infiltration. This does not accurately describe the physical situation. However, it provides a simple method of estimating one-dimensional infiltration governed by a boundary at zero soil-water potential when flow takes place predominantly in an almost saturated zone (Youngs 1988).

Philip's infiltration equation is

$$I = S\sqrt{t} + At \tag{3}$$

where S is sorptivity ($\mathrm{cm/hr}^{1/2}$), t is time (hr), and A is a permeability coefficient (cm/hr).

This equation gives infiltration as a function of time, and predicts the cumulative infiltration to be proportional to the square root of time during the early stages of infiltration, and the infiltration rate to approach the hydraulic conductivity of the saturated soil as time increases. Sorptivity is related to the wetting front potential in the Green and Ampt model by the approximate expression (Philip 1957b; Youngs 1968)

$$S = \sqrt{2K_s H_f(\theta_s - \theta_i)} \tag{4}$$

Both Green and Ampt and Philip equations require a value for the mean wetting front water potential (H_f). Bouwer (1964) suggested H_f in the Green and Ampt model could be determined from measurable soil physical properties. He proposed that by using the unsaturated hydraulic conductivity – water content relation, H_f could be determined by integrating the relation

$$H_f = \int_{h_i}^{h_0} K_r dh \qquad (5)$$

where h_i is the initial matric potential (m), h_0 is the matric potential at saturation, K_r is the relative hydraulic conductivity ($K_r = K/K_s$) and h is the matric potential (m). While this equation did give good predictions with numerical simulations, it was based on an analogy with horizontal flow rather than on formal reasoning (Neuman 1976), and theoretical justification was not given until Mein and Farrel (1974) reported an attempt to derive it analytically.

Mein and Larson (1973) developed a relationship where H_f can be determined from the matric potential vs. hydraulic conductivity relationship by integrating

$$H_f = \frac{1}{K_s} \int_{K_i}^{K_s} h dK \qquad (6)$$

where K_i is the initial hydraulic conductivity (m/s), and K is the unsaturated hydraulic conductivity (m/s). Similar to Bouwer's method, this model relies on unsaturated hydraulic conductivity data. However, integration is effected over the limits of matric potential in Bouwer's method, while the Mein-Larson equation is integrated over the limits of conductivity.

After reading a manuscript by Neuman (1976), where he attempted to theoretically derive Bouwer's equation, Parlange (1976) proposed an interesting derivation, valid at small values of time, that may constitute an improvement over Bouwer's original equation:

$$H_f = \frac{1}{2} \int_{h_i}^{h_0} \left(1 + \frac{\theta - \theta_i}{\theta_s - \theta_i} \right) K_r dh \qquad (7)$$

where h_i is the initial wetting front matric potential (m), h_0 is the matric potential at saturation (0 m), θ_s is the saturated water content (v/v), θ_i is the initial water content (v/v), K_r is relative hydraulic conductivity (m/s), and h is the matric potential (m). If we now invoke the concept of the Green and Ampt wetting profile (Green and Ampt 1911), then $\theta = \theta_s$, and the equation immediately reduces to Bouwer's equation (Neuman 1976).

The Bouwer model (eq. 5) and Mein and Larson model (eq. 6) require the K-h relationship to estimate H_f. The Neuman model (eq. 7) requires, in addition, the h-θ relationship. All of these relationships are not commonly available, which limits the general use of these equations. However, if H_f could be estimated from K_s, infiltration estimates could be made more easily.

Assuming that soil pores are cylindrical capillary tubes, the saturated hydraulic conductivity of a soil can be shown to be

$$K_s = \left(\frac{\rho_\omega g}{4\alpha\eta}\right)\theta_s \overline{r^2} \tag{8}$$

where ρ_ω is the density of water (1000 kg/m^3), g is the gravitational constant (9.81m/s^2), η is the viscosity of water (0.001 kg m^{-1} s^{-1}), θ_s is the saturated water content (v/v), and $\overline{r^2}$ is the average pore radius (m^2). The dimensionless factor α accounts for the shape of the soil pores and the fact that the flow paths of soil water are not straight lines. For linear, cylindrical capillary tubes, $\alpha = 2$ (Hillel 1982).

For soils, because water follows tortuous paths, α must be multiplied by a tortuosity factor, κ. It is defined as the square of the ratio of the actual lengths of the tortuous paths that water follows, L_{actual}, over the straight-line distance of water movement, L.

$$\kappa = \left(\frac{L_{actual}}{L}\right)^2 \tag{9}$$

If we imagine that water follows the outer surface of a soil particle, then the straight-line distance is L = D, with D the diameter of the particle, and the actual length of the curved path of the water is $L_{actual} = 0.5\pi D$. The tortuosity factor is thus

$$\kappa = \left(\frac{L_{actual}}{L}\right)^2 = (0.5\pi)^2 = 2.47 \tag{10}$$

The geometry factor is $\alpha = 2\kappa = 4.9 \approx 5$. Using numerical values for the various constants, for eq. 8,

$$K_s(\mathrm{m/s}) = 5\times10^5\theta\,\overline{r^2} \tag{11}$$

The relationship between pore radius and matric potential is

$$r = \frac{2\sigma}{\rho_\omega g h} \tag{12}$$

where r is the pore radius (m), σ is surface tension of water (0.072 J/m^2), and h is the matric potential (m). By combining these two equations (eq. 11 and eq. 12) we have

$$K_s = 10^{-4}\frac{\theta_s}{\overline{h^2}} \tag{13}$$

or

$$\bar{h} = 10^{-2}\sqrt{\frac{\theta_s}{K_s}} \tag{14}$$

where $\bar{h}$ is the 'average' matric potential (m) corresponding to 'average' pore radius, $\bar{r}$ (m). In eq. 11, the wetting front potential, H_f, represents, in some sense, the "average" water potential change across the wetting front, where soil water content changes from θ_i to θ_s. The "average" matric potential given by eq. 14, on the other hand, represents the "average" matric potential of water conducting pores in a saturated soil. If we assume that for infiltration into an initially dry soil, the wetting front potential (H_f) is proportional to the "average" matric potential of eq. 14, we have

$$H_f = (C)10^{-2}\sqrt{\frac{\theta_s}{K_s}} \tag{15}$$

where C is a proportionality constant. This equation will be referred to as the K_s model.

3.2 Materials and Methods

3.2.1 Simulation Evaluation

Twenty-two soils with their hydraulic functions previously described in the literature (Yates *et al.* 1992) were used to evaluate the equations for predicting H_f. Wetting front potential (H_f) estimations were made for these soils using the K_s model and by three methods found in the literature (Bouwer 1964; Mein and Larson 1973; and Neuman 1976). The H_f estimations were used to calculate sorptivity according to equation 4, and Philip's infiltration equation (equation 3) is used to predict the total amount of water entering the soil over a period of 1hr in the horizontal direction. Under these conditions, equation 3 reduces to I (1hr) = S. Using the same soils and boundary conditions, infiltration was predicted numerically, using the infiltration routine of the Chemflow model (Nofziger *et al.* 1989). Results of the numerical simulation were compared to those predicted using different estimates of H_f. In order to evaluate the K_s model over a range of water contents, hydraulic functions of Pachapa loam were taken from the literature (Yates *et al.* 1992) and used to produce an infiltration water content relationship. Numerical solutions for infiltration at initial soil water contents from residual to saturation were calculated. These values were compared to infiltration calculated with the Philip equation over the same water content range using H_f predicted by the K_s model.

3.2.2 Field Evaluation

Models for estimating H_f were also evaluated against field measurements from three experimental sites.

The St. Vincent site (est. 1998) site is located 1.6 km east of St. Vincent, approximately 160 km northeast of Edmonton. The 0.4-ha site is located on an east facing slope with a relatively constant eastward 5% slope across the entire site. The soil conditions on the St. Vincent site vary with slope position. The soil belongs to the Lacorey soil series and is an Orthic Gray Luvisol. The Ap horizon is a loam texture, with 48/37/15% sand, silt and clay, respectively, while the underlying Bt_1 is a fine sandy loam with 59/21/19% sand, silt and clay, respectively. It is a typical well drained soil developed on a moderately fine till. There is no strong evidence of an Ah and Ae horizon in this soil because of the mechanical mixing by cultivation. The thickness of the B horizon and depth to underlying C horizons varies with slope position. In the lower slope position, the soil profile is more characteristic of the Fergy soil series, which is an Eluviated Black Chernozem, developed on similar parent material to the Lacorey series.

The site layout consists of a randomized complete block design with four replicates. Treatments include 40 Mg/ha cattle manure applied in spring or fall. The control plot received no manure and barley has been grown on all plots annually since establishment of the site. For the purpose of this study, plots with cattle manure applied in the spring and the control plots are used for infiltration measurements.

The Lethbridge (est. 1973) site is located at the Agriculture and Agri-food Canada Lethbridge Research Center. The soil type is a Calcareous Orthic Dark Brown Chernozemic clay loam soil with approximately 28/42/30% sand, silt and clay, respectively, on a relatively flat site. Four rates of cattle manure are applied to the site each year: 0, 30, 60, and 90 Mg/ha/yr and incorporated with a cultivator. Manure treatments are in a randomized complete block design with five replicate plots that have received manure since 1973. Barley was grown on the site from 1974

– 1995, canola in 1996, corn in 1997, triticale in 1998 and 1999, and barley again in 2000 – 2002.

The Breton Classical Plots (est. 1930) are located 3 km southeast of Breton, AB. The soil on the site is an Orthic Gray Luvisol mapped as a Breton loam series. The site layout consists of strips with 10 fertilizer treatments (control, cattle manure applied every fifth year, NPKS, NS, lime, lime + P, P, manure + NPKS, and NPKS) and two cropping rotations within each treatment (a five year rotation: wheat–oat–barley–legume–legume, and a two year: wheat -fallow rotation). Infiltration measurements were only conducted on the control, manure, and NPKS plots, with the crops currently in oats, hay, and wheat of the wheat fallow rotation.

Field infiltration measurements were conducted on a number of different soils using a single ring infiltrometer. A metal ring 30 cm in diameter was pushed 10 cm into the ground and a constant head of water (5 cm) was maintained using a Marriott tube (Figure 3-3). Infiltration was measured for a period of 1-hr, during which the cumulative infiltration was determined at approximately 1-5 min intervals, depending on the rate of water drop in the tube. Initial water content was found using a Trace Systems TDR (Soil Moisture Equip. Corp., Santa Barbara, California) prior to an infiltration measurement to a depth of 10 cm, at 3 locations just outside the ring. Saturated water contents were assumed to be equal to the porosity of the soil. Bulk density was found by taking a core sample 10 cm in depth and 5.4 cm in diameter. Infiltration measurements were conducted in the fall 2001on all three sites, after harvest and prior to cultivation, and again in the spring 2002 for the Breton and St. Vincent sites only, prior to any field operations.

Saturated hydraulic conductivity was estimated using Method 2 described by Wu *et al.* (1999 (Appendix 2). A linear equation was fit to the last 15 - 20 min of the cumulative infiltration curve. The slope of the fitted straight line is used in the calculation of K_s. Another method, also described by Wu *et al.* (1999) (Appendix 1), in which the entire cumulative infiltration curve is used, was tested for comparison, but Method 2 was used to estimate K_s for infiltration predictions.

At each site where an infiltration measurement was conducted, a soil sample was taken and used to determine the soil water characteristic curve. Soil was collected to a depth of 10 cm outside of the ring at 3 locations and a composite sample was taken. Soil samples were passed through a 2 mm sieve and packed into a brass ring, 3 cm deep with a diameter of 5.5 cm, using a hydraulic press. The amount of soil packed into each ring was predetermined to match the bulk density of the field soil. Packed samples were placed in Tempe cells (Soil Moisture Equip. Santa Barbara, California) and allowed to saturate for approximately 5 days. Pressure was applied to the cells at increasing values of 2, 5, 10 kPa. Samples were removed from the Tempe cells and placed on pressure plates for the remaining pressures of 30, 100 and 1500 kPa to complete the soil water characteristics curve measurement.

The unsaturated hydraulic conductivity – water potential relationship was found indirectly from the soil water release curves by use of the van Genuchten (1980)equation. This relationship was used to estimate wetting front potential for the models described by Bouwer (1964), Mein and Larson (1973), and Neuman (1976).

Infiltration measurements at different initial water contents were conducted on a clay loam soil. Three 30-cm rings were placed in the soil 1 m apart to a depth of 15 cm. Infiltration was measured at the antecedent water content of $\theta = 0.10$, determined by TDR to a depth of 10 cm, for 1 hr in all three rings. Rings were left in place and infiltration measurements were repeated when the soil water content fell to $\theta = 0.25$. The same procedure was repeated again when the soil water content fell to $\theta = 0.40$. Immediately following this measurement, infiltration was again measured using saturation as the starting water content. Infiltration values at the various water contents were used to develop an infiltration – water content relationship. This relationship was predicted using the K_s model to estimate H_f and used in the Philip equation to predict 1-hr infiltration at each of the water contents. The predicted values were compared to experimental measurements.

3.3 Results

In Figure 3-2, values calculated for 1-hr infiltration using the four methods of estimating H_f (Bouwer 1964, Mein-Larson 1973, Neuman 1976 and the K_s model) are compared with numerical predictions for the 22 soils found in the literature. A 1:1 relationship was inserted along with a regression line for the data points. All methods gave predicted values with considerable variation. The methods of Bouwer (1964), Mein and Larson (1973), and Neuman (1976), overestimated numerical infiltration for all soil types.

The proportionality constant, C=0.1, gave the best prediction of cumulative infiltration for the K_s model (eq. 15). Therefore, the model becomes $H_f = 10^{-3}\frac{\sqrt{(\theta_s - \theta_i)}}{K_s}$, and is used for all predictions of H_f when using the Ks model in this study. Infiltration predicted by all models showed considerable variation, as compared to the numerical simulation (Figure 3-2).

Values for cumulative infiltration measured on the three sites in fall 2001 and on two sites in spring 2002 were compared to the calculated cumulative infiltration predicted by the Philip equation. The results are shown in Figures 3-3 and 3-4. The K_s model and the three methods described above were used to estimate H_f and used in equation 4 to estimate the sorptivity required by the Philip equation. For fall 2001 and spring 2002, predicted infiltration values were almost always higher than the values measured on all three sites. Exceptions were: measured values for the Breton site in spring 2002 were closer to predicted values than those taken on the other sites, and measured values for the St. Vincent site were closer to predicted values in fall 2001 than in spring 2002.

Measured values for cumulative infiltration on the three experimental sites were compared with values predicted by the Green and Ampt equation (Figure 3-5), using the H_f estimates calculated previously. As with values calculated using the Philip equation, the majority of predicted values were greater than measured values, but closer agreement was observed. Values predicted with the Philip equation are plotted against those found using the Green and Ampt equation in Figure 3-6. The Philip equation consistently gives values higher than the Green and Ampt equation. The Philip equation predicts values 18% higher on average than the Green and Ampt equation, with an R^2 of 0.99.

Sorptivity – water content relationships for Pachapa loam found numerically and using the K_s model are shown in Figure 3-7a. Predicted values are slightly lower than numerical values, but the shapes of the two curves are nearly identical. The difference in values appears to be constant at all water contents. Scaling the predicted curve by 14% results in nearly identical curves as shown in Figure 3-7b. The infiltration – water content relationship found through field measurements and compared to predicted values using the K_s model and the Philip equation, are shown in Figure 3-8a. The predicted values are higher than the measured values at all water contents, except at the highest initial water content. Figure 3-8b shows that the predicted curve scaled down to pass through the measured value at $\theta = 0.25$ water content gives a close fit to experimental observations.

3.4 Discussion

The K_s model proposed is a quick, easy and reliable method for estimating wetting front potential during infiltration. The numerical simulations show that the K_s model produces good estimates of H_f and S, with errors comparable to other models that rely on more detailed information from soil hydraulic properties. H_f and S values estimated with the K_s model allow better predictions of measured infiltration than other models tested in this study. Significant variations were found in the predicted infiltration values of all the models. A major advantage of the K_s model over other methods is in the ease of obtaining the H_f parameter without the necessity of producing detailed soil hydraulic functions. The errors that arise in estimating these functions when measurements are not available can give misleading results.

When calculating H_f with models requiring h-θ and/or K-θ relationships (Mein and Larson 1973; Bouwer 1964), soil hydraulic functions for undisturbed soils should be used. In many cases, however, h-θ relations are measured with disturbed soil samples. Differences in the soil hydraulic functions between disturbed and undisturbed field soil samples may introduce additional uncertainties in the predicted H_f. This could partially account for the observed low accuracy of these models in our field assessment (Figure 3-4). However, we also observed a low correlation between predicted infiltration and numerical simulations where identical hydraulic functions were used for both numerical simulation and predicted models (Figure 3-2). Comparable correlation coefficients between numerical simulation evaluation and field evaluation suggest that these models for predicting H_f are not sensitive to inaccuracies in detailed soil hydraulic functions. The use of exact soil hydraulic functions in our numerical simulation evaluation did not produce noticeable improvement in the performance of these models.

Soils in the landscape experience fluctuating water contents during the seasons and infiltration does not always take place in a dry soil. The ability to predict infiltration at all water contents is required. The K_s model can be used to predict infiltration as a function of initial soil water content. The error in prediction is consistent throughout the range of water contents. As is shown in Figure 3-7a, the K_s model provides a relationship between water content and sorptivity that very closely matches the numerical solution. Although, for this particular soil an underestimation was found, the error is consistent at all water contents. The percent error at a particular value of water content can be used to correct the predicted sorptivity – water content relationship at other water content values. For example, a single measurement of infiltration at an arbitrary water content can be performed and compared to a predicted value. The difference between the prediction and this infiltration measurement can then be used to adjust the predicted sorptivity - water content curve at all soil water contents. We have verified this assertion with field measurements of infiltration – water content relationships (Figure 3-8a). The measured infiltration – water content relationship closely follows that of the predicted values (Figure 3-8b) except at the highest water content. Soils in the landscape experience changes due to swelling of clays and changes to the surface conditions due to cultivation, rainfall and other physical forces. The lower accuracy in measured infiltration values at high water content could be partially caused by changes to the physical properties of the soil during the measurement process, such as slaking of soil aggregates and the plugging of soil pores.

A limiting factor when using the K_s model is the accuracy of estimation of saturated hydraulic conductivity. The ring infiltrometer was used to develop a cumulative infiltration curve, from which K_s was found by using Method 2 described by Wu *et al.* (1999) (Appendix 1). This method gives a reasonable estimation. However, when using the K_s values derived from this method, infiltration predictions were higher than values measured, possibly due to an overestimation of K_s. Another method described by Wu *et al.* (1999) uses the entire cumulative infiltration curve to obtain a K_s value (Appendix 1). Wu *et al* (1999) claimed that K_s values determined by both methods were comparable; our attempt at using Method 1 produced values for K_s that did not support the infiltration measured (Appendix 2).

In the field, conditions of the soil can vary. In a dry soil, cracks at the surface provide macro channels for water movement in the initial stages of infiltration, while as infiltration proceeds, soils can swell and reduce infiltration rates. In addition, surface seals may form as infiltration measurements proceed. Cumulative infiltration curves fitted to field data do not always provide a shape that can be represented by an equation. Although K_s was overestimated, Method 2 did provide reasonable results for the soils where infiltration was measured.

Wetting front potential is generally associated with the Green and Ampt infiltration model, but is also related to the sorptivity required by the Philip model through equation 4 (Philip 1957b; Youngs 1968). Sorptivity is a function of the wetting front potential. The H_f parameter estimated by the K_s model can be effectively applied to calculate the sorptivity of the Philip equation. The Green and Ampt model gave slightly lower infiltration values and correlated more closely with measured results than the Philip model (Figure 3-6). On average, the Green and Ampt model gave values approximately 18% lower than the Philip model, as indicated in Figure 6. This is consistent with results by Swartzenburger and Youngs (1972), who found the Philip equation was never more than 15.1% higher than Green Ampt values, and by other researchers who also found close agreement between the Philip and Green and Ampt equations (e.g., Youngs 1968; Whisler and Bouwer 1970).

3.5 Conclusion

The K_s model is an effective and reliable method for estimating the wetting front potential required by infiltration models. Results using the K_s model were as good or better than results using the other methods tested. A significant advantage in using the K_s model is the elimination of the need for detailed hydraulic functions that are difficult to measure and can introduce significant errors when estimated. The K_s model at all water contents provides a useful, easy and versatile tool for predicting infiltration when using either the Green and Ampt or Philip infiltration models. Parameters required by the K_s and infiltration models can be obtained using a simple ring infiltrometer. Predicted infiltration curves can be adjusted by a single measured value to extend the range of reasonably accurate predicted values for infiltration.

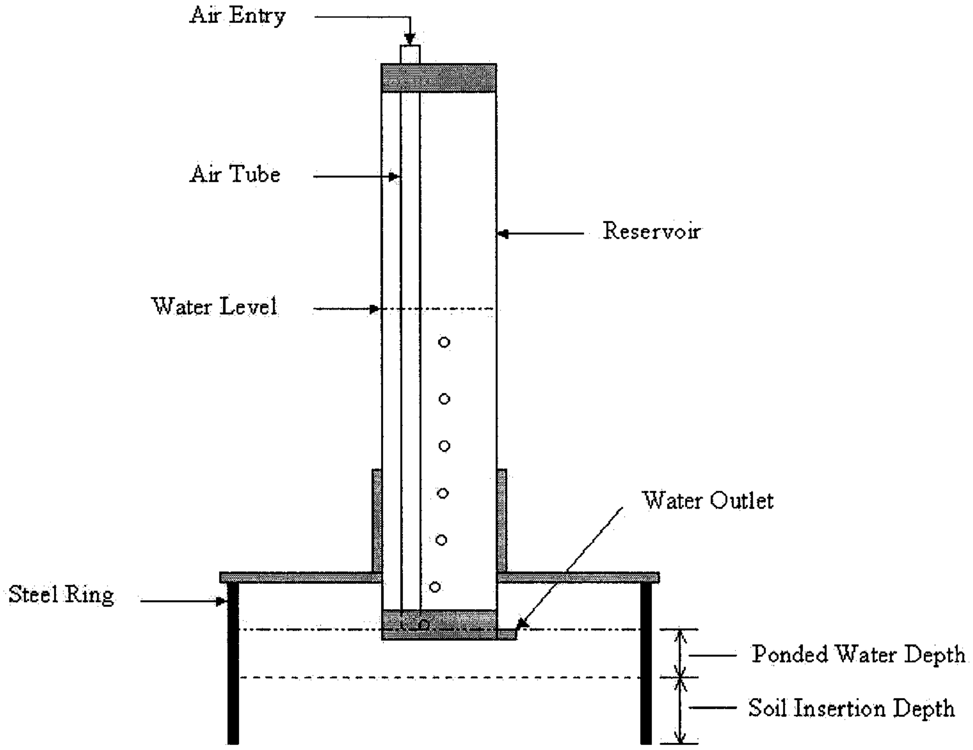


Figure 3-1: Schematic diagram of the single ring infiltrometer and water supply.

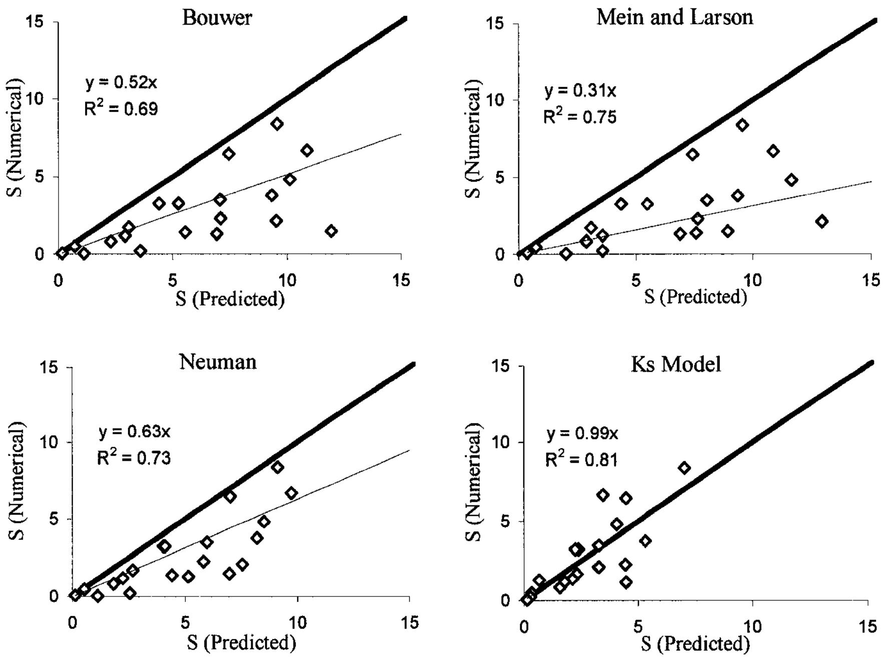


Figure 3-2: Comparison of infiltration in the horizontal direction over a 1-hr time period using the Philip equation with four methods of estimating H_f, and a numerical solution using 22 soils with their hydraulic functions described in the literature (Yates *et al.* 1992). (The dark line is a 1:1 relationship and the light line is the regression of the data points.)

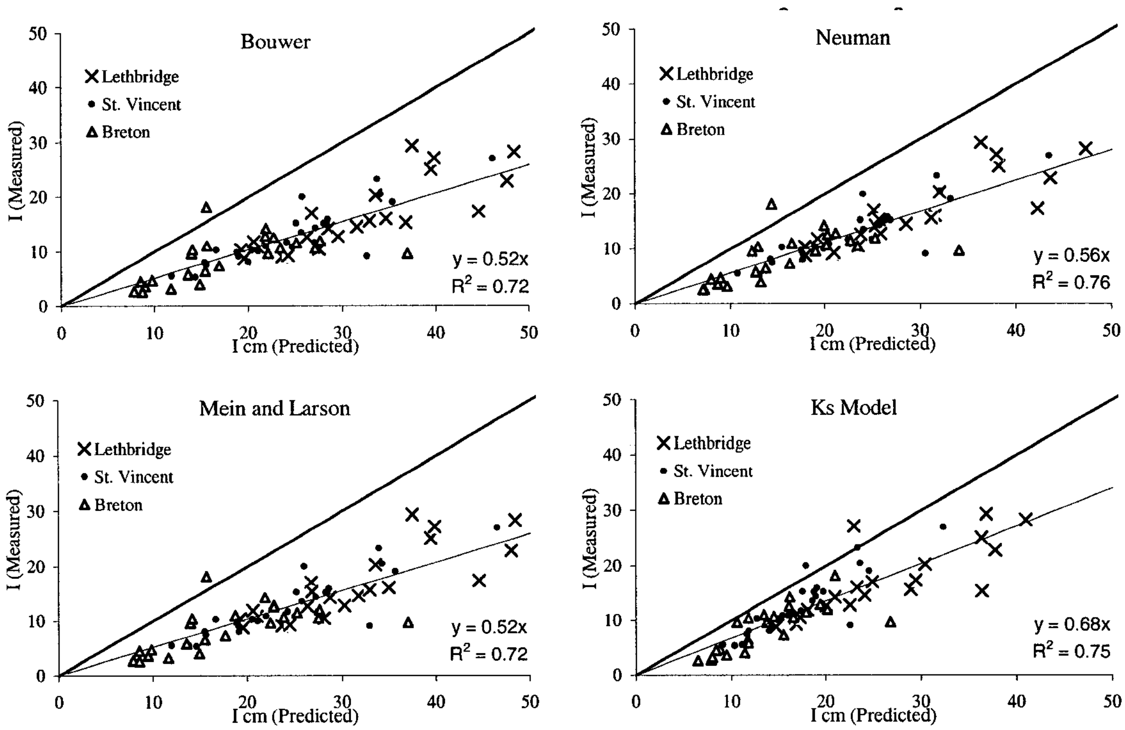


Figure 3-3: Comparison of measured vs. predicted infiltration using the Philip equation and four methods of estimating H_f over a period of 1 hr. Measurements conducted in the fall 2001. (The dark line is a 1:1 relationship and the light line is the regression of the data points.)

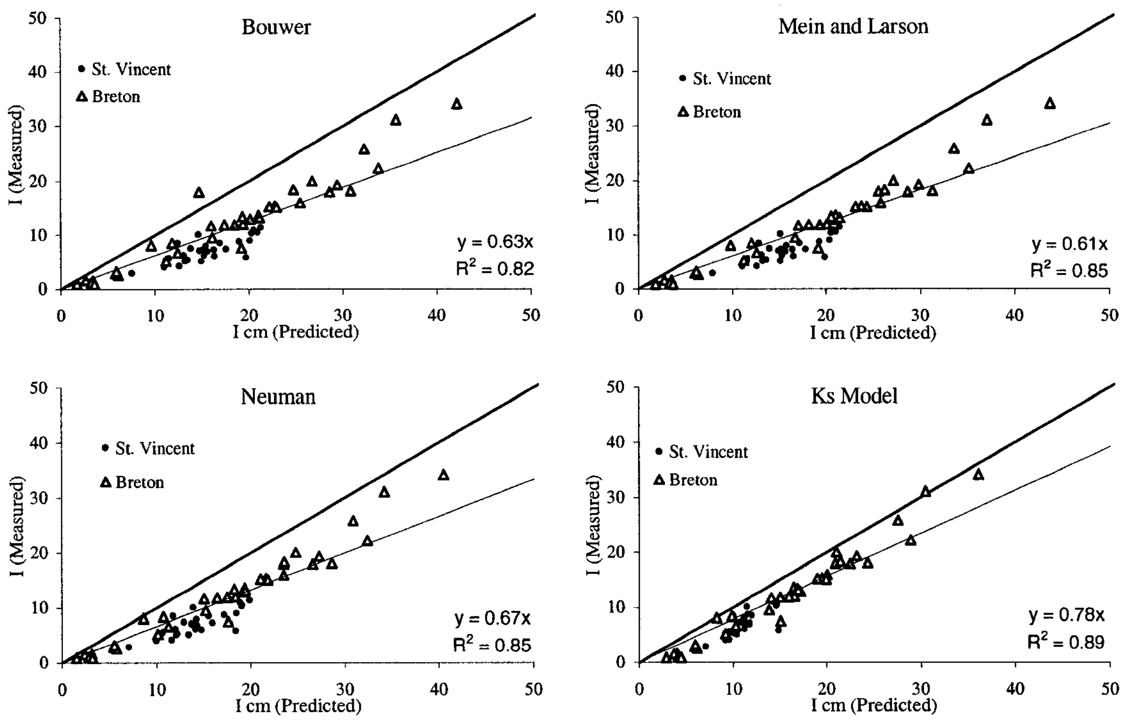


Figure 3-4: Comparison of measured vs. predicted infiltration using the Philip equation and four methods of estimating H_f, over a period of 1 hr. Measurements conducted in the spring 2002. (The dark line is a 1:1 relationship and the light line is the regression of the data points.)

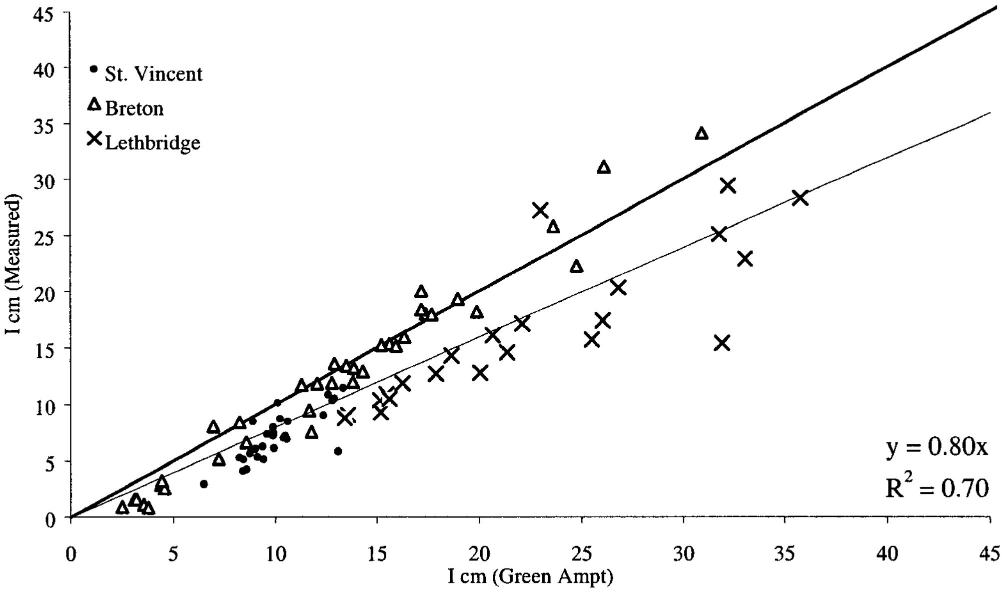


Figure 3-5: Comparison of measured 1-hr infiltration on three sites in the fall 2001, and predicted infiltration using the Green and Ampt equation when using the K_s model to estimate H_f. (The dark line indicates a 1:1 relationship, while the light line is the regression of the data points).

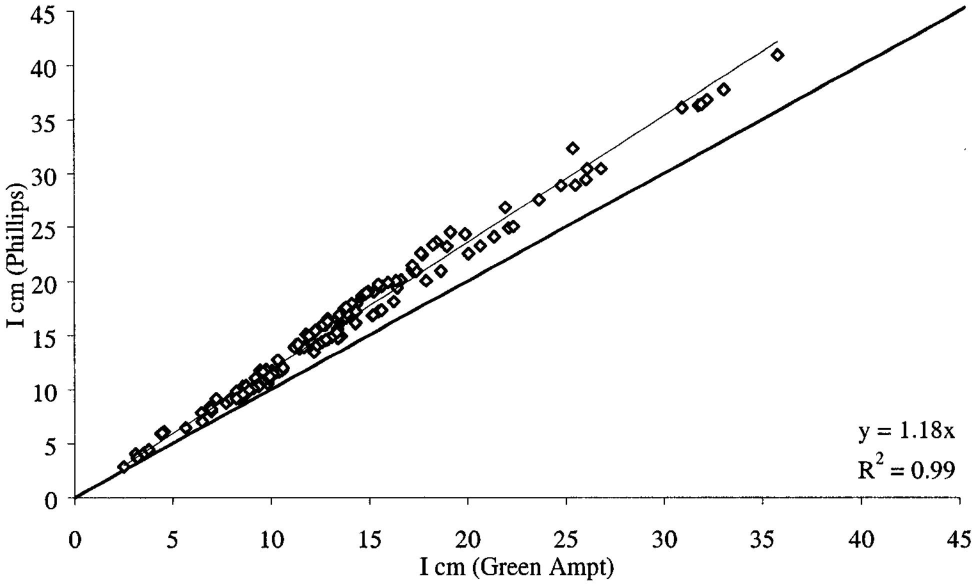


Figure 3-6: Comparison of infiltration predicted with the Green and Ampt and Philip equations when using the K_s model to estimate H_f. (The dark line indicates a 1:1 relationship, while the light line is the regression of the data points).

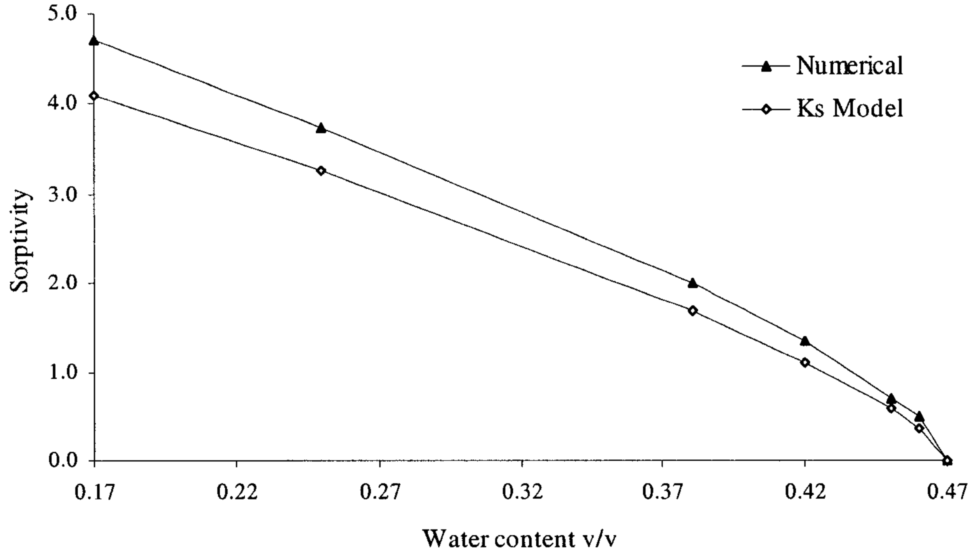


Figure 3-7a: Sorptivity – water content relationship of Pachapa loam using the K_s model and the numerical prediction.

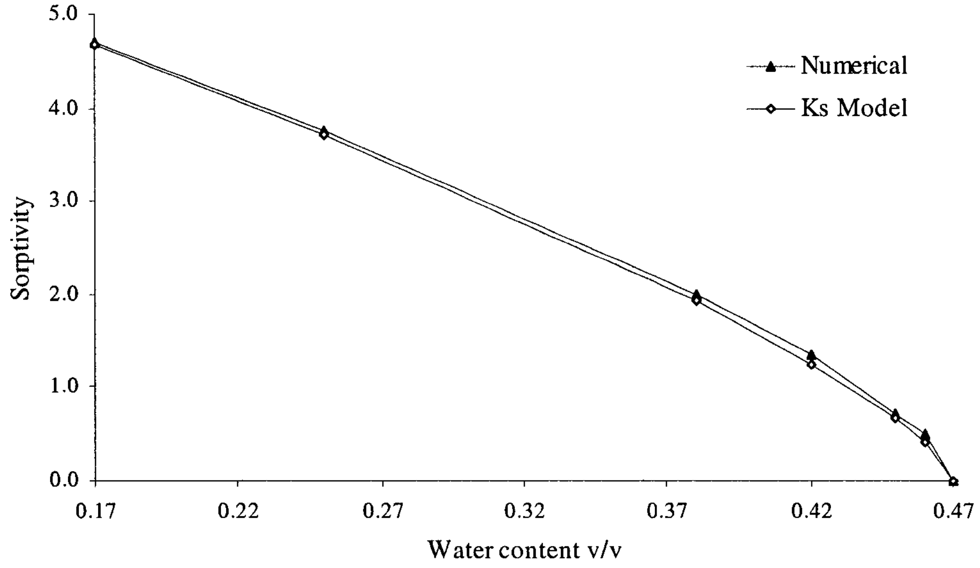


Figure 3-7b: Scaled sorptivity – water content relationship of Pachapa loam using the K_s model and a numerical prediction.

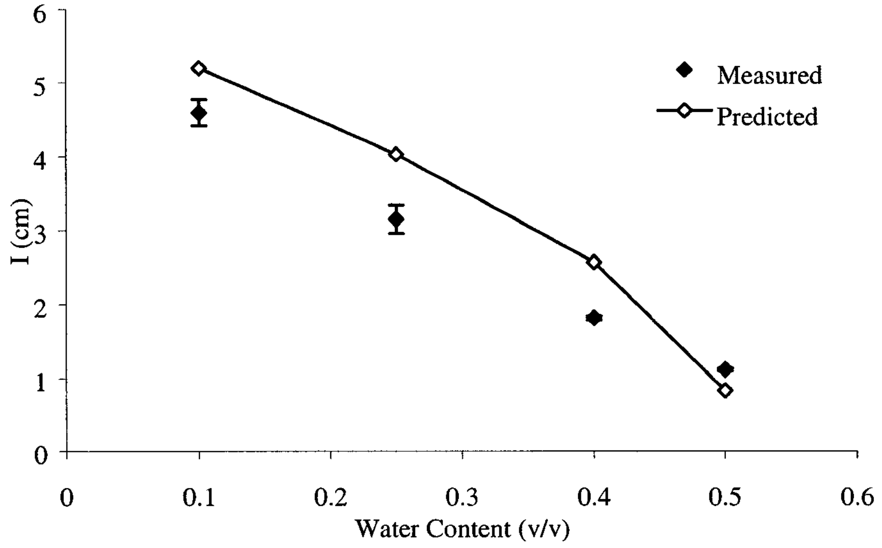


Figure 3-8a: Infiltration – water content relationship predicted with the K_s model and Philip equation, and through field infiltration measurements.

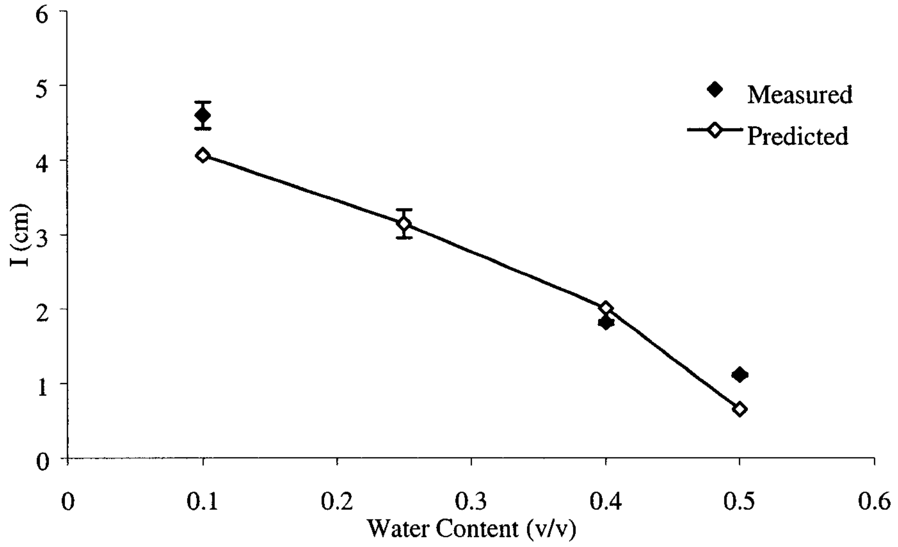


Figure 3-8b: Predicted infiltration – water content curve scaled to pass through the measured point at 0.25 v/v.

3.6 References

Bouwer, H. 1964. Unsaturated flow in ground water hydraulics. J. Hydraul. Div. Amer. Soc. Civ. Eng. 90:121-144.

Brooks, R.H., and Corey, A.T. 1964. Hydraulic properties of porous media. Hydrology paper no. 3, Civil Engineering Dep., Colorado State Univ., Fort Collins, Colorado.

Green, W.H., and Ampt, G.A. 1911. Studies on soil physics: I. Flow of air and water through soils. J. Agr. Sci. 4: 1-24.

Hillel, D. 1982. Introduction to soil physics. Academic Press. New York.

Kutilek, M., and Nielson, D. 1994. Soil hydrology, Catena Verlag, Cremlingen – Destedt, Germany. 370 p.

Mein, R.G., and Farrell, D.A. 1974. Determination of wetting front suction in the Green – Ampt equation. Soil Sci. Soc. Amer. Proc. 6: 872-876.

Mein, R.G., and Larson, C.L. 1973. Modeling infiltration during a steady rain. Water Resour. Res. 9: 384-394.

Mualem, Y. 1976 . A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resour. Res. 12: 513-522.

Neuman, S.P. 1976. Wetting front pressure head in the infiltration model of Green and Ampt. Water Resour. Res. 12: 564 – 566.

Nofziger, D.L., Rajender, K., and Nayudu, S.K.. 1989. Chemflow, One dimensional water and chemical movement in unsaturated soils. Computer program. Dep. Agron. Oklahoma State Univ.

Philip, J.R. 1957a. The theory of infiltration: 1. The infiltration equation and its solution. Soil Sci. 83: 345-357.

Philip, J.R. 1957b. The theory of infiltration: 2. The profile of infinity. Soil Sci. 83: 435-448.

Richards, L.A. 1931. Capillary conduction of liquids through porous mediums. Physics 1: 318-333.

Swartzendruber, D., and Youngs, E.G. 1972. A comparison of physically – based infiltration equations. Soil Sci. 117: 165-167.

van Genuchten, M.Th. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Amer. J. 44: 892-898.

Whisler, F.D., and Bouwer, H. 1970. Comparison of methods for calculating vertical drainage and infiltration for soils. J. Hydrol. 10: 1-19.

Wu, L., Pan, L., Mitchell, J., and Sanden, B. 1999. Measuring saturated hydraulic conductivity using a generalized solution for single – ring infiltrometers. Soil Sci. Soc. Amer. J. 63: 788-792.

Yates, S.R., van Genuchten, M.Th., Warrick, A.W., and Leij, F.J. 1992. Analysis of measured, predicted, and estimated hydraulic conductivity using the TETC computer program. Soil Sci. Soc. Amer. J. 56: 347-354.

Youngs, E.G. 1968. An estimation of sorptivity for infiltration studies from moisture moment considerations. Soil Sci. 106:157-163.

Youngs, E.G. 1988. Hydraulic conductivity profiles of two clay soils. J. Soil Sci. 39:341-345.

Chapter 4.

4.1 Synthesis

A number of studies have been conducted regarding the effects of cattle manure applications on the physical properties of soils (Miller 1999; Darwish *et al.* 1995; Sweeten and Mathers 1985; Unger and Stewart 1974). Most studies are specific to an area or soil type and vary in manure application rate and duration and in other agronomic conditions. Some studies have focused on a specific property such as aggregate stability (Mazurak *et al.* 1977), while others have examined a wide range of soil physical properties (Miller *et al.* 2002). A review summarizing the major effects of manure application on soil physical properties has been written by Sweeten and Mathers (1985).

This study found that the application of cattle manure has a positive effect on most soil physical properties. Through its contribution to soil organic content, the addition of manure decreases soil bulk density, increases the stability of aggregates, increases field capacity and wilting point, and increases soil water infiltration rates.

While most of the changes to soil physical properties are desirable, the increase in field capacity and wilting point does not necessarily lead to an increase in plant available water holding capacity. In the present study, it was found that plant available water was not affected, or was negatively affected, by an increase in soil organic matter content. This is contrary to a study by Hudson (1994) where an increase in soil organic matter content increased the amount of available water in soils of similar texture. In our study, changes in soil organic matter content were a result of manure application. However, Hudson (1994) studied unamended soils consisting of native organic matter. Manure-derived soil organic matter consists of material in various stages of decomposition. It is possible that, in our study, the manure did not have sufficient time to produce an effect similar to that of native organic matter. However, seventy five years of manure application on the Breton site did not appear sufficient to increase the plant available water holding capacity. Therefore, we speculate that organic matter derived from manure does not behave like native soil organic matter with respect to its effect on soil structure and water retention characteristics.

The primary result of manure application to soil is an increase in organic matter content. This increase can be represented by a linear relationship where the net soil organic matter content increase is a function of the rate of manure applied, the duration or years of application, and soil texture. Furthermore, changes to soil physical properties such as bulk density and water retention can be related to net changes in soil organic matter by a linear relationship.

Simple statistical models give us the ability to predict future events under a controlled set of conditions. In dealing with cattle manure applications, numerous models have been developed to deal with nutrient transformations and carbon cycling, but very little information regarding the soil physical properties exists. The results of this study indicate that simple linear statistical models can be developed to predict an increase in soil organic matter content as a function of manure application rate, duration and soil texture. Furthermore, changes to soil physical properties as a result of a manure application can be related to changes in soil organic matter content through a linear relationship.

Models provide a tool to predict changes that are likely to occur when manure is added. Care must be taken when using these models; significant errors can arise in predicting changes beyond the range in which these models have been tested. The use of models to predict the properties of manure treated soil is also limited by the conditions under which the models have been developed. That is, soil conditions in the experimental soil must be similar to soil conditions to which the model is applied. For example, when testing the water retention models of Khaleel *et al.* (1981) with data from this study, most data fit the model until net changes in organic matter content increased over 2.6%. Beyond this point the model provided a non-linear relationship between water retention and net increase in soil organic matter content. This model was developed on soil conditions where the net increases in soil organic matter content were low, and extrapolating beyond these values led to non-linear behavior.

Modeling infiltration is often required when dealing with watershed models that attempt to predict runoff, erosion and other hydrological processes. The Philip and Green and Ampt infiltration models have been well accepted and provide reasonable predictions of infiltration. However, the parameters required for these models, especially the wetting front potential (H_f) of the Green and Ampt equation and the sorptivity (S) of the Philip equation are not easily found. The K_s model described and evaluated in this study provides a simpler and equally effective method for estimating the S and H_f parameters, compared to methods found in the literature. Tested on a wide range of soils, both through numerical simulation and field measurements, the K_s model is effective at predicting H_f at all water contents.

A required input for the K_s model is the saturated hydraulic conductivity (K_s). Saturated hydraulic conductivity can be found with a single ring infiltrometer, that at the same time can provide a field-measured infiltration value. Predicting an infiltration water content curve using the K_s model, and scaling the curve to pass through the field measured infiltration value, provides an accurate representation of infiltration occurring in the field at all water contents.

This K_s model provides us with a simple and effective method to determine the parameters necessary for infiltration models. By simplifying the methods and equations, predictions for a wide range of conditions can be predicted without the extensive work, cost and knowledge previously required.

4.2 References

Darwish, O.H., Persaud, N., and Martens, D.C. 1995. Effect of long-term application of animal manure on physical properties of three soils. Plant Soil 176:289-295.

Hudson, D.B. 1994. Soil organic matter and available water holding capacity. J. Soil Water Cons. 49:189-194.

Mazurak, A.P., Chesnin, L., and Thijeel, A. 1977. Effects of beef cattle manure on water stability of soil aggregates. Soil Sci. Soc. Amer. J. 41:613-615.

Miller, J.J., Sweetland, N.J., and C. Chang 1999. Impact on long-term manure applications on soil physical properties. Farming for the Future Research Program. Final technical report. Project 970793. Alberta Agriculture Research Institute.

Miller, J.J, Sweetland, N.J., and Chang, C. 2002. Hydrological properties of a clay loam soil after long-term cattle manure application. J. Environ. Qual. 31:989-996.

Sweeten, J.M., and Mathers, A.C. 1985. Improving soils with livestock manure. J. Soil Water Conserv. 40:826-830.

Unger, P.W., and Stewart, B.A. 1974. Feedlot waste effects on soil conditions and water evaporation. Soil Sci. Soc. Amer. Proc. 38:954-958.

Appendix 1

Measuring saturated hydraulic conductivity using a generalized solution for single-ring infiltrometers (Wu *et al.* 1999).

Method 1.

The generalized infiltration equation is fitted to the measured infiltration curve.

$$I = At + B\sqrt{t} \tag{1}$$

where I is cumulative infiltration, and A and B are characterizing constants describing the shape of the curve.

Solve eq. 2 for K_{S}:

$$K_s = \frac{\Delta\theta\lambda_s}{T_c} \tag{2}$$

where

$$\lambda_s = \frac{1}{2}\left[\sqrt{(H + G^*)^2 + 4G^*C} - (H + G^*)\right] \tag{3}$$

$$T_c = \frac{1}{4}\left(\frac{Ba}{bA}\right)^2 \tag{4}$$

$$C = \frac{1}{4\Delta\theta}\left(\frac{B}{b}\right)^2 \tag{5}$$

and

$$G^* = d + r/2 \tag{6}$$

In equations (1) through (6), a and b are dimensionless constants ($a = 0.9084$, $b = 0.1682$), H is the ponded depth, d is the ring insertion depth, r is the radius of the ring, θ is the soil water content, and $\Delta\theta$ is the change in water content from initial to saturation.

Method 2

Method 2 is based on the assumption that the last part of the infiltration event has reached steady state.

The linear equation is fitted to the linear part of the infiltration curve:

$$I = At + c \tag{1}$$

where I is cumulative infiltration, A and c are characterizing constants describing the straight line, and t is time.

Solve eq. 2 for K_{s}:

$$K_s = A/(af) \tag{2}$$

where

$$f \approx \frac{H + \frac{1}{\alpha}}{G^*} + 1 \tag{3}$$

$$G^* = d + r/2 \tag{4}$$

In equations (1) through (5), K_s is the saturated hydraulic conductivity, H is the ponded depth, r is the radius of the ring, d is the ring insertion depth, and a = 0.908 (dimensionless).

Soil	α value suggested by Elrick et al. (1988)
	1/cm
Sand	0.36
Loamy Sand	0.36
Bernio fine sand	0.36
Loam	0.12
Arlington fine sandy loam	0.12
Yolo clay	0.04

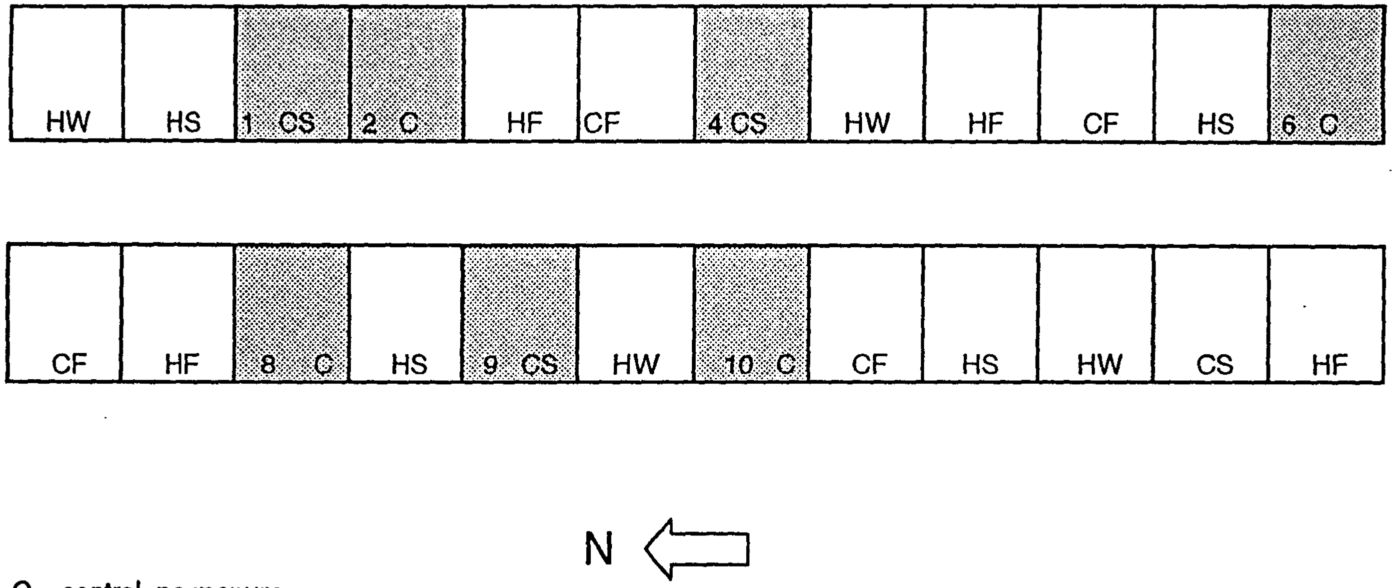
Appendix 2

Plot diagrams of the St. Vincent, Lethbridge and Breton research sites.

Appendix 2.1

Plot diagram for the St. Vincent site.

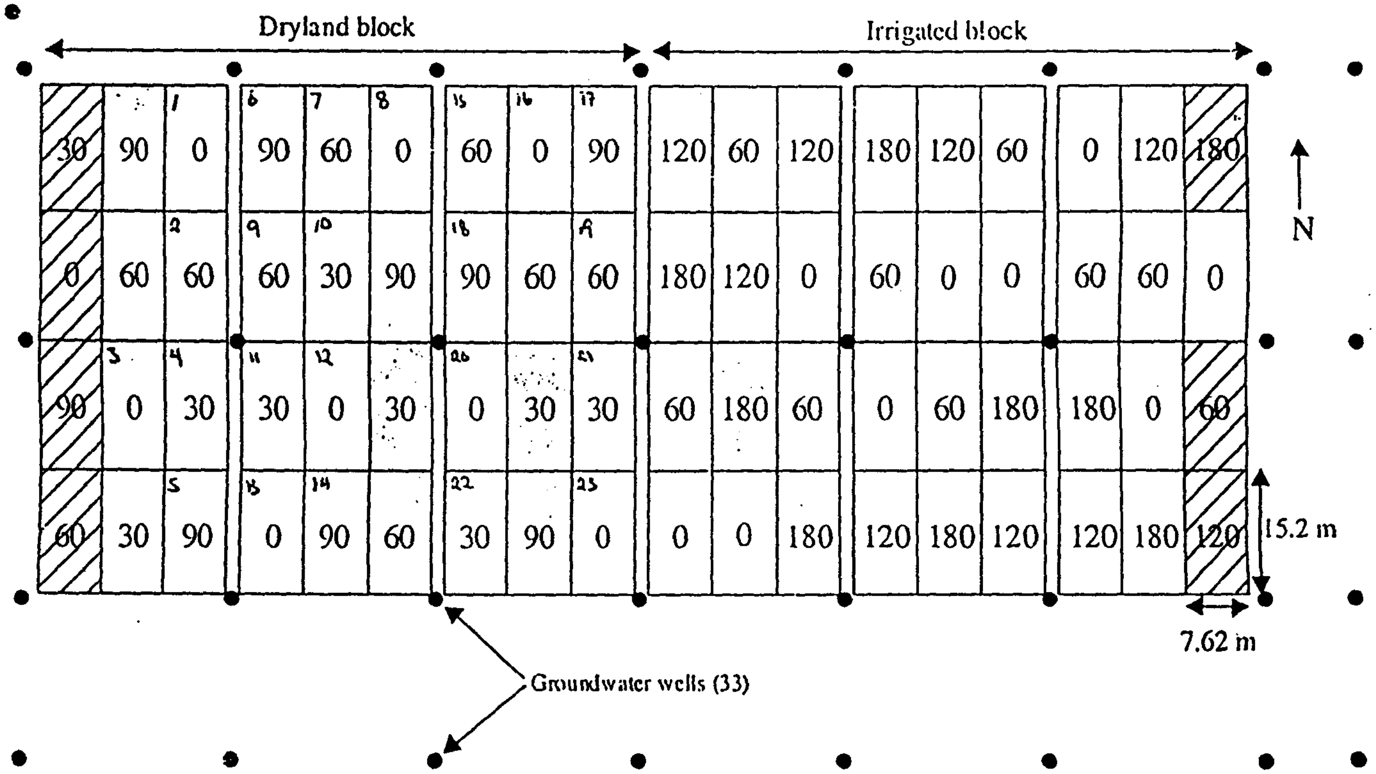
Manure Project - St. Vincent site



HW	HS	1 CS	2 C	HF	CF	4 CS	HW	HF	CF	HS	6 C
CF	HF	8 C	HS	9 CS	HW	10 C	CF	HS	HW	CS	HF

C = control, no manure
Hx = Hog manure
Cx = Cattle manure
xS = spring application
xF = fall application
xW = winter application

Lethbridge Research Centre Long-term Manure Site



The numbers indicate the annual manure application rate in Mg/ha on a wet-weight basis.

▨ Plots removed in the fall, 1990. ☐ Manure application discontinued after 1986.

Appendix 2.2

Plot diagram for the Lethbridge site.

Appendix 2.3
Plot diagram for the Breton site.

Breton Plot Cropping and Fertilizers

Series

F	E (EAST)	D	C	B	A	
CHECK	CHECK	CHECK	CHECK	CHECK	CHECK	1
MANURE	MANURE	MANURE	MANURE	MANURE	MANURE	2
0-22-46-5.5	90-22-46-5.5	50-22-46-5.5	75-22-46-5.5	50-22-46-5.5	0-22-46-5.5	3
0-0-46-5.5	90-0-46-5.5	50-0-46-5.5	75-0-46-5.5	50-0-46-5.5	0-0-46-5.5	4
CHECK	CHECK	CHECK	CHECK	CHECK	CHECK	5
LIME	LIME	LIME	LIME	LIME	LIME	6
0-22-46-0	90-22-46-0	50-22-46-0	75-22-46-0	50-22-46-0	0-22-46-0	7
0-22-46-5.5	0-22-46-5.5	0-22-46-5.5	0-22-46-5.5	0-22-46-5.5	0-22-46-5.5	8
0-22-46-5.5	90-22-46-5.5	50-22-46-5.5	75-22-46-5.5	50-22-46-5.5	0-22-46-5.5	9
0-22-0-5.5	90-22-0-5.5	50-22-0-5.5	75-22-0-5.5	50-22-0-5.5	0-22-0-5.5	10
CHECK	CHECK	CHECK	CHECK	CHECK	CHECK	11
HAY-2	WHEAT	WHEAT	OATS	BLY/HAY	HAY-1	

Appendix 3

K_s values found using Method 1 and Method 2 of Wu *et al.* 1999

Lethbridge			St. Vincent		
	K_s (cm/hr)			K_s (cm/hr)	
Plot ID	Method 1	Method 2	Plot ID	Method 1	Method 2
9	1.6	8.5	1.1	0.2	2.1
7	0.4	4.7	1.2	3.9	7.0
21	0.9	5.8	1.3	1.5	8.1
19	1.0	6.1	1.4	1.4	2.9
16	1.0	6.6	4.1	0.1	4.0
27	0.5	4.6	4.2	1.9	3.2
29	2.1	7.9	4.3	3.2	5.6
36	0.9	5.9	4.4	1.1	5.5
11	2.8	9.8	9.1	7.6	13.5
18	1.1	5.9	9.2	4.0	19.7
15	5.6	9.3	9.3	1.5	8.5
35	4.6	10.4	2.1	2.5	12.0
28	1.7	8.4	2.2	0.6	5.7
10	6.0	19.0	2.3	2.0	9.0
17	5.2	18.6	2.4	0.0	4.6
25	7.6	14.3	6.1	2.5	3.5
14	2.6	10.4	6.2	3.1	12.8
34	12.9	13.2	6.3	1.9	6.6
12	15.3	21.4	6.4	0.3	3.9
13	19.7	19.6	8.1	3.3	12.6
20	3.4	10.0	8.2	1.9	7.7
26	7.7	18.0	8.3	4.2	9.3
33	10.8	13.0	8.4	3.7	9.1
			10.1	3.1	9.2
			10.2	3.1	9.8
			10.3	1.4	6.3
			10.4	1.0	8.2

Appendix 4

Raw data for the St. Vincent, Lethbridge and Breton sites.

Data includes the following analysis:

- Infiltration
- Bulk Density
- Organic Matter
- Water Stable Aggregates
- Water Retention

Appendix 4.1

Cumulative infiltration values for the St. Vincent site.

Treatment Mg/ha/yr	Crop	Plot ID	Infiltration (cm) Fall 2001	 Spring 2002
0	Barley	6	9.1	7.0
0	Barley	6	13.6	7.4
0	Barley	6	10.3	5.1
0	Barley	6	5.5	8.5
0	Barley	8	20.6	2.9
0	Barley	8	10.9	8.5
0	Barley	8	7.5	5.3
0	Barley	8	23.3	1.0
0	Barley	2	8.1	5.1
0	Barley	2	10.3	6.3
0	Barley	2	8.1	6.9
0	Barley	2	9.8	4.1
0	Barley	10	14.4	10.3
0	Barley	10	15.3	4.2
0	Barley	10	11.0	6.1
0	Barley	10	15.3	11.4
	Average		12.1	6.3
	Std. Dev.		4.8	2.7
	Std. Err.		1.2	0.7
40	Barley	1	5.5	5.5
40	Barley	1	10.9	6.1
40	Barley	1	11.7	7.4
40	Barley	1	5.3	1.2
40	Barley	4	19.1	7.2
40	Barley	4	27.0	5.3
40	Barley	4	13.9	7.2
40	Barley	4	20.0	10.5
40	Barley	9	11.7	8.0
40	Barley	9	7.0	8.5
40	Barley	9	15.7	9.0
40	Barley	9	.	10.9
	Average		13.4	7.2
	Std. Dev.		6.7	2.6
	Std. Err.		2.0	0.7

Appendix 4.2

Cumulative infiltration values for the Lethbridge site.

Treatment Mg/ha/yr	Crop	Plot ID	Infiltration (cm) Fall 2001
0	Barley	L9	14.3
0	Barley	L7	9.1
0	Barley	L21	10.4
0	Barley	L19	10.9
0	Barley	L16	11.9
0	Barley	L29	8.8
0	Barley	L27	12.7
0	Barley	L36	9.3
	Average		10.9
	Std. Dev.		1.9
	Std. Err.		0.7
30	Barley	L11	16.1
30	Barley	L18	10.5
30	Barley	L15	15.8
30	Barley	L35	12.8
30	Barley	L28	14.6
	Average		14.0
	Std. Dev.		2.3
	Std. Err.		1.0
60	Barley	L10	29.4
60	Barley	L17	25.1
60	Barley	L14	20.3
60	Barley	L25	17.1
60	Barley	L34	15.7
	Average		21.5
	Std. Dev.		5.7
	Std. Err.		2.5
90	Barley	L12	28.3
90	Barley	L13	22.9
90	Barley	L20	15.4
90	Barley	L33	17.4
90	Barley	L26	27.2
	Average		22.3
	Std. Dev.		5.7
	Std. Err.		2.6

Appendix 4.3

Cumulative infiltration values for the Breton site.

Treatment Mg/ha/yr	Crop	Plot ID	Infiltration (cm) Fall 2001	Infiltration (cm) Spring 2002
Manure	Oats	2A	9.3	15.9
Manure	Oats	2A	18.8	20.0
Manure	Oats	2A	12.7	18.1
Manure	Oats	2A	.	19.3
	Average		13.6	18.3
	Std. Dev.		4.8	1.8
	Std. Err.		2.4	0.9
NPKS	Oats	3A	3.6	12.9
NPKS	Oats	3A	12.9	12.0
NPKS	Oats	3A	7.3	9.5
NPKS	Oats	3A	.	18.0
	Average		7.9	13.1
	Std. Dev.		4.7	3.6
	Std. Err.		2.3	1.8
Control	Oats	5A	11.5	15.3
Control	Oats	5A	4.0	19.5
Control	Oats	5A	6.5	11.9
Control	Oats	5A	.	11.8
	Average		7.3	14.6
	Std. Dev.		3.9	3.6
	Std. Err.		1.9	1.8
Manure	Hay	2B	11.0	22.3
Manure	Hay	2B	9.6	34.1
Manure	Hay	2B	12.6	25.8
Manure	Hay	2B	.	31.1
	Average		11.1	28.3
	Std. Dev.		1.5	5.3
	Std. Err.		0.7	2.6
NPKS	Hay	3B	10.7	5.2
NPKS	Hay	3B	10.5	17.9
NPKS	Hay	3B	9.6	13.0
NPKS	Hay	3B	.	7.6
	Average		10.3	10.9
	Std. Dev.		0.6	5.7
	Std. Err.		0.3	2.9
Control	Hay	5B	5.1	13.4
Control	Hay	5B	3.6	18.3
Control	Hay	5B	3.4	15.2
Control	Hay	5B	.	11.7
	Average		4.0	14.7
	Std. Dev.		0.9	2.8
	Std. Err.		0.5	1.4

Treatment Mg/ha/yr	Crop	Plot ID	Infiltration (cm) Fall 2001	Infiltration (cm) Spring 2002
Manure	Wheat	2E	18.2	6.7
Manure	Wheat	2E	9.9	8.4
Manure	Wheat	2E	10.4	8.1
Manure	Wheat	2E	.	13.2
	Average		12.8	9.1
	Std. Dev.		4.7	2.9
	Std. Err.		2.3	1.4
NPKS	Wheat	3E	5.8	2.9
NPKS	Wheat	3E	2.7	2.6
NPKS	Wheat	3E	4.5	1.6
NPKS	Wheat	3E	.	3.2
	Average		4.3	2.6
	Std. Dev.		1.6	0.7
	Std. Err.		0.8	0.4
Control	Wheat	5E	2.6	1.6
Control	Wheat	5E	3.2	1.1
Control	Wheat	5E	3.0	0.9
Control	Wheat	5E	.	0.9
	Average		2.9	1.1
	Std. Dev.		0.3	0.3
	Std. Err.		0.2	0.2

Appendix 4.4

Bulk density values for the St. Vincent site.

Treatment (Mg/ha/yr)	Crop	Plot ID	Bulk Density (Mg/m^3)	
			0-10 cm	10-20 cm
0	Barley	6	1.22	1.27
0	Barley	6	1.23	1.31
0	Barley	6	1.17	1.33
0	Barley	6	1.32	1.31
0	Barley	8	1.19	1.25
0	Barley	8	1.16	1.16
0	Barley	8	1.25	1.06
0	Barley	8	1.26	1.27
0	Barley	2	1.27	1.52
0	Barley	2	1.35	1.35
0	Barley	2	1.33	1.52
0	Barley	2	1.30	1.41
0	Barley	10	1.27	1.15
0	Barley	10	0.96	1.25
0	Barley	10	1.28	1.45
0	Barley	10	1.16	1.43
	Average		1.23	1.32
	Std. Dev.		0.09	0.13
	Std. Err.		0.02	0.03
40	Barley	1	1.26	1.39
40	Barley	1	1.23	1.42
40	Barley	1	1.21	1.44
40	Barley	1	1.32	1.46
40	Barley	4	1.14	1.42
40	Barley	4	1.27	1.15
40	Barley	4	1.52	1.49
40	Barley	4	1.32	1.45
40	Barley	9	1.23	1.18
40	Barley	9	1.23	1.09
40	Barley	9	1.26	0.94
40	Barley	9	1.28	0.96
	Average		1.27	1.28
	Std. Dev.		0.09	0.21
	Std. Err.		0.02	0.05

Appendix 4.5

Bulk density values for the Lethbridge site.

Treatment (Mg/ha/yr)	Crop	Plot ID	Bulk Density (Mg/m^3) 0-10 cm	Bulk Density (Mg/m^3) 10-20 cm
0	Barley	L9	1.21	1.45
0	Barley	L7	1.26	1.33
0	Barley	L21	1.23	1.33
0	Barley	L19	1.22	1.38
0	Barley	L16	1.25	1.39
0	Barley	L29	1.18	1.34
0	Barley	L27	1.18	1.23
0	Barley	L36	1.23	1.26
	Average		1.22	1.34
	Std. Dev.		0.03	0.07
	Std. Err.		0.01	0.02
30	Barley	L11	1.28	1.36
30	Barley	L18	1.04	1.31
30	Barley	L15	1.15	1.33
30	Barley	L35	1.16	1.34
30	Barley	L28	1.20	1.28
	Average		1.17	1.32
	Std. Dev.		0.09	0.03
	Std. Err.		0.04	0.01
60	Barley	L10	1.05	1.33
60	Barley	L17	0.97	1.21
60	Barley	L14	1.02	1.33
60	Barley	L25	1.00	1.23
60	Barley	L34	1.01	1.01
	Average		1.01	1.22
	Std. Dev.		0.03	0.13
	Std. Err.		0.01	0.06
90	Barley	L12	0.97	1.27
90	Barley	L13	0.87	1.15
90	Barley	L20	1.00	1.17
90	Barley	L33	0.78	1.10
90	Barley	L26	0.95	1.11
	Average		0.91	1.16
	Std. Dev.		0.09	0.07
	Std. Err.		0.04	0.03

Appendix 4.6

Bulk density values for the Breton site.

Treatment	Crop	Plot ID	Bulk Density (Mg/m^3)		Treatment	Crop	Plot ID	Bulk Density (Mg/m^3)	
			0-10 cm	10-20 cm				0-10 cm	10-20 cm
Manure	Oats	2A	1.09	1.15	Control	Hay	5B	1.20	1.26
Manure	Oats	2A	0.98	1.16	Control	Hay	5B	1.21	1.20
Manure	Oats	2A	1.10	1.33	Control	Hay	5B	1.16	1.43
Manure	Oats	2A	1.26	1.13	Control	Hay	5B	1.13	1.15
Manure	Oats	2A	0.95	1.18	Control	Hay	5B	1.42	1.18
	Average		1.07	1.19		Average		1.22	1.25
	Std. Dev.		0.12	0.08		Std. Dev.		0.11	0.11
	Std. Err.		0.05	0.03		Std. Err.		0.05	0.05
NPKS	Oats	3A	1.21	1.34	Manure	Wheat	2E	0.98	1.20
NPKS	Oats	3A	1.24	1.20	Manure	Wheat	2E	1.29	1.11
NPKS	Oats	3A	1.29	1.18	Manure	Wheat	2E	1.31	1.34
NPKS	Oats	3A	1.02	1.35	Manure	Wheat	2E	1.05	1.23
NPKS	Oats	3A	1.16	1.23	Manure	Wheat	2E	1.24	1.37
	Average		1.18	1.26		Average		1.17	1.25
	Std. Dev.		0.10	0.08		Std. Dev.		0.15	0.11
	Std. Err.		0.04	0.04		Std. Err.		0.07	0.05
Control	Oats	5A	1.20	1.62	NPKS	Wheat	3E	1.47	1.27
Control	Oats	5A	1.18	1.33	NPKS	Wheat	3E	1.17	1.23
Control	Oats	5A	1.54	1.48	NPKS	Wheat	3E	1.31	1.49
Control	Oats	5A	1.02	1.32	NPKS	Wheat	3E	1.17	1.25
Control	Oats	5A	1.44	1.33	NPKS	Wheat	3E	1.28	1.22
	Average		1.28	1.42		Average		1.28	1.29
	Std. Dev.		0.21	0.13		Std. Dev.		0.12	0.11
	Std. Err.		0.09	0.06		Std. Err.		0.06	0.05
Manure	Hay	2B	1.07	1.02	Control	Wheat	5E	1.20	1.42
Manure	Hay	2B	0.92	1.15	Control	Wheat	5E	1.36	1.53
Manure	Hay	2B	1.21	1.16	Control	Wheat	5E	1.24	1.48
Manure	Hay	2B	1.17	1.13	Control	Wheat	5E	1.35	1.41
Manure	Hay	2B	1.03	1.13	Control	Wheat	5E	1.18	1.45
	Average		1.08	1.12		Average		1.27	1.46
	Std. Dev.		0.12	0.06		Std. Dev.		0.08	0.05
	Std. Err.		0.05	0.02		Std. Err.		0.04	0.02
NPKS	Hay	3B	0.98	1.06					
NPKS	Hay	3B	1.36	1.26					
NPKS	Hay	3B	1.07	1.12					
NPKS	Hay	3B	1.06	1.31					
NPKS	Hay	3B	1.18	1.11					
	Average		1.13	1.17					
	Std. Dev.		0.14	0.11					
	Std. Err.		0.06	0.05					

Appendix 4.7

Organic matter values for the St. Vincent site.

Treatment (Mg/ha/yr)	Crop	Plot ID	Organic Matter (%) 0-10 cm	Organic Matter (%) 10-20 cm
0	Barley	2	2.7	2.2
0	Barley	6	3.6	4.4
0	Barley	8	4.7	5.6
0	Barley	10	4.9	5.8
	Average		4.0	4.5
	Std. Dev.		1.0	1.7
	Std. Err.		0.6	1.0
40	Barley	1	3.1	2.8
40	Barley	4	3.0	2.7
40	Barley	9	5.8	6.6
	Average		4.0	4.0
	Std. Dev.		1.6	2.3
	Std. Err.		0.8	1.1

Appendix 4.8

Organic matter values for the Lethbridge site.

Treatment (Mg/ha/yr)	Crop	Plot ID	Organic Matter (%) 10cm	Organic Matter (%) 20cm
0	Barley	L9	3.8	2.3
0	Barley	L7	2.9	2.2
0	Barley	L21	5.1	2.5
0	Barley	L19	3.0	1.9
0	Barley	L16	3.8	2.5
0	Barley	L29	4.2	3.0
0	Barley	L27	2.9	2.5
0	Barley	L36	4.1	3.2
	Average		3.7	2.5
	Std. Dev.		0.8	0.4
	Std. Err.		0.3	0.1
30	Barley	L11	5.8	2.8
30	Barley	L18	5.6	3.3
30	Barley	L15	5.2	2.8
30	Barley	L35	4.2	3.0
30	Barley	L28	5.0	4.1
	Average		5.2	3.2
	Std. Dev.		0.6	0.5
	Std. Err.		0.3	0.2
60	Barley	L10	7.5	5.1
60	Barley	L17	7.8	5.0
60	Barley	L14	7.5	4.9
60	Barley	L25	5.8	7.8
60	Barley	L34	9.4	5.3
	Average		7.6	5.6
	Std. Dev.		1.3	1.2
	Std. Err.		0.6	0.5
90	Barley	L12	8.7	6.5
90	Barley	L13	9.5	5.1
90	Barley	L20	7.6	5.8
90	Barley	L33	9.4	5.3
90	Barley	L26	8.8	6.6
	Average		8.8	5.8
	Std. Dev.		0.8	0.7
	Std. Err.		0.3	0.3

Appendix 4.9

Organic matter values for the Breton site.

Treatment	Crop	Plot ID	Organic Matter (%)	
			0-10 cm	10-20 cm
Manure	Oats	2A	3.4	2.4
NPKS	Oats	3A	2.6	2.6
Control	Oats	5A	1.7	1.5
Manure	Hay	2B	4.2	1.9
NPKS	Hay	3B	2.9	1.8
Control	Hay	5B	2.1	1.8
Manure	Wheat	2A	3.4	1.5
NPKS	Wheat	3A	1.4	0.7
Control	Wheat	5A	1.1	0.6

Appendix 4.10

Water stable aggregate values for the St. Vincent site.

Treatment (Mg/ha/yr)	Crop	Plot ID	Water Stable Aggregates (%) 0-10 cm	10-20 cm
0	Barley	10	22.6	43.7
0	Barley	2	27.6	33.1
0	Barley	6	30.8	31.5
0	Barley	8	21.2	29.2
	Average		25.5	34.4
	Std. Dev.		4.5	6.4
	Std. Err.		2.2	3.2
40	Barley	1	23.2	32.4
40	Barley	4	20.7	33.2
40	Barley	9	21.9	29.5
	Average		21.9	31.7
	Std. Dev.		1.3	1.9
	Std. Err.		0.7	1.1

Appendix 4.11

Water stable aggregate values for the Lethbridge site.

Treatment (Mg/ha/yr)	Crop	Plot ID	Water Stable Aggregates (%) 0-10 cm	Water Stable Aggregates (%) 10-20 cm
0	Barley	L9	6.90	33.26
0	Barley	L7	7.72	35.60
0	Barley	L21	12.35	28.01
0	Barley	L19	12.38	20.25
0	Barley	L16	10.66	19.01
0	Barley	L29	8.20	20.31
0	Barley	L27	12.60	14.73
0	Barley	L36	12.20	15.30
	Average		10.38	23.31
	Std. Dev.		2.39	7.99
	Std. Err.		0.85	2.82
30	Barley	L11	6.20	30.25
30	Barley	L18	10.28	20.50
30	Barley	L15	11.02	20.24
30	Barley	L35	15.30	30.20
30	Barley	L28	10.20	14.55
	Average		10.60	23.15
	Std. Dev.		3.24	6.88
	Std. Err.		1.45	3.08
60	Barley	L10	22.10	27.10
60	Barley	L17	9.87	21.52
60	Barley	L14	16.85	32.24
60	Barley	L25	9.90	19.55
60	Barley	L34	11.83	31.50
	Average		14.11	26.38
	Std. Dev.		5.30	5.73
	Std. Err.		2.37	2.56
90	Barley	L12	12.31	29.35
90	Barley	L13	19.40	19.00
90	Barley	L20	14.55	25.26
90	Barley	L33	15.76	.
90	Barley	L26	13.71	32.56
	Average		15.15	26.54
	Std. Dev.		2.69	5.85
	Std. Err.		1.20	2.92

Appendix 4.12

Water stable aggregate values for the Breton site.

Treatment (Mg/ha/yr)	Crop	Plot ID	Water Stable Aggregates (%) 0-10 cm	Water Stable Aggregates (%) 10-20 cm
Manure	Oats	2A	37.98	44.87
NPKS	Oats	3A	36.58	26.24
Control	Oats	5A	31.56	22.80
Manure	Hay	2B	69.21	56.06
NPKS	Hay	3B	47.34	44.25
Control	Hay	5B	37.37	29.29
Manure	Wheat	2A	19.84	23.09
NPKS	Wheat	3A	15.80	20.13
Control	Wheat	5A	15.78	13.68

Appendix 4.13

Water retention values for the St. Vincent site.

Treatment	Crop	Plot ID	Water Retention (%)			
			0-10 cm		10-20 cm	
(Mg/ha/yr)			Field Capacity	Wilting Point	Field Capacity	Wilting Point
0	Barley	2	30.0	12.7	29.0	11.5
0	Barley	6	28.0	11.8	28.0	12.0
0	Barley	8	29.0	13.4	27.0	13.0
0	Barley	10	32.0	12.4	29.0	14.0
	Average		29.8	12.6	28.3	12.6
	Std. Dev.		1.7	0.7	1.0	1.1
	Std. Err.		0.9	0.3	0.5	0.6
40	Barley	1	35.0	11.5	30.0	11.5
40	Barley	4	28.0	13.8	29.0	14.0
40	Barley	9	28.0	13.6	29.0	13.0
	Average		30.3	13.0	29.3	12.8
	Std. Dev.		4.0	1.3	0.6	1.3
	Std. Err.		2.3	0.7	0.3	0.7

Appendix 4.14

Water retention values for the Lethbridge site.

Treatment	Crop	Plot ID	Water Retention (%)			
			0-10 cm		10-20 cm	
(Mg/ha/yr)			Field Capacity	Wilting Point	Field Capacity	Wilting Point
0	Barley	L9	34.3	21.2	28.9	21.8
0	Barley	L7	40.9	23.7	28.4	23.2
0	Barley	L21	31.5	21.2	28.0	22.7
0	Barley	L19	32.3	18.5	27.0	21.3
0	Barley	L16	40.3	17.9	27.9	20.7
0	Barley	L29	36.7	20.0	28.5	20.6
0	Barley	L27	45.2	24.9	27.3	21.6
0	Barley	L36	35.0	18.2	28.5	20.2
	Average		37.0	20.7	28.1	21.5
	Std. Err.		4.8	2.6	0.7	1.1
	Std. Dev.		1.7	0.9	0.2	0.4
30	Barley	L11	42.5	24.1	28.5	20.8
30	Barley	L18	42.0	21.9	26.6	19.9
30	Barley	L15	35.4	20.0	29.6	22.4
30	Barley	L35	39.1	22.1	27.9	23.2
30	Barley	L28	43.8	34.6	30.3	20.8
	Average		40.5	24.5	28.6	21.4
	Std. Err.		3.4	5.8	1.4	1.3
	Std. Dev.		1.5	2.6	0.6	0.6
60	Barley	L10	38.1	31.5	27.8	20.5
60	Barley	L17	37.9	27.0	26.4	19.9
60	Barley	L14	40.5	29.7	27.4	24.8
60	Barley	L25	43.0	29.5	27.9	25.5
60	Barley	L34	44.3	35.1	27.7	25.1
	Average		40.8	30.6	27.4	23.1
	Std. Err.		2.9	3.0	0.6	2.7
	Std. Dev.		1.3	1.3	0.3	1.2
90	Barley	L12	49.1	28.2	22.5	16.3
90	Barley	L13	41.0	29.8	26.6	19.7
90	Barley	L20	55.0	40.2	26.1	20.2
90	Barley	L33	39.3	30.1	24.8	20.5
90	Barley	L26	.	.	25.2	20.8
	Average		46.1	32.1	25.0	19.5
	Std. Err.		7.3	5.5	1.6	1.8
	Std. Dev.		3.7	2.7	0.7	0.8

Appendix 4.15

Water retention values for the Breton site.

Treatment	Crop	Plot ID	Water Retention (%)			
			0-10 cm		10-20 cm	
			Field Capacity	Wilting Point	Field Capacity	Wilting Point
Manure	Oats	2A	29.3	18.1	27.2	19.5
NPKS	Oats	3A	27.2	16.4	27.1	17.2
Control	Oats	5A	24.1	15.1	25.2	17.2
Manure	Hay	2B	28.5	19.1	28.4	18.5
NPKS	Hay	3B	28.4	18.2	27.2	17.2
Control	Hay	5B	26.1	18.4	27.1	17.5
Manure	Wheat	2A	28.4	18.2	27.5	17.2
NPKS	Wheat	3A	28.1	15.1	25.4	16.3
Control	Wheat	5A	26.4	13.4	25.2	15.2

References

1. Elrick, D.E., W.D. Reynolds., and K.A. Tan. 1988. A new analysis for the constant head well permeameter technique. P.88-95. *In* P.J. Wierenga and D. bachelet (ed.) Validation of flow and transport models for the unsaturated zone: Conf. Proc. Ruidoso, NM 23-26 May 1988. Res. Rep. 88-SS-04. Dep. of Agron. And Hortic., New Mexico State Univ., Las Cruces.

2. Wu, L., Pan, L., Mitchell, J., and Sanden, B. 1999. Measuring saturated hydraulic conductivity using a generalized solution for single – ring infiltrometers. Soil Sci. Soc. Amer. J. 63: 788-792.