Czech University of Life Sciences Prague

Faculty of Agrobiology, Food and Natural Resources

Department of Water Resources

Evaluation of saturated and near saturated hydraulic conductivity of soil under different tillage treatments

Diploma Thesis

Olubisi Adio

Sustainable Agriculture and Food Security

Ing. Kamila Báťková, MSc., PhD.

Declaration

I declare that the Diploma Thesis "Evaluation of saturated and near saturated hydraulic conductivity of soil under different tillage treatments" is my own work and all the sources I cited in it are listed in References.

Prague, 12 April 2019 Signature _______ ____________________

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Evaluation of saturated and near saturated hydraulic conductivity of soil under different tillage treatments

Summary

Water is an indispensable factor required for the growth and development of crops. The movement of water is largely dependent on soil physical and hydraulic properties such as hydraulic conductivity which governs the ease at which water moves through the soil. The aim of this research was to evaluate the saturated *Ks* and near saturated *K(h)* hydraulic conductivity of soil under conventional (CT), reduced (RT) and no-tillage(NT), and to test the null hypothesis that the hydraulic conductivities under tillage or no-tillage do not differ.

The measurement of *K(h)* was done with the use of Mini Disk infiltrometer (METER Group, Inc.) at pressure heads -5, -3 and -1 cm respectively for each of the tillage treatments. *Ks* was determined in the field with the use of Pressure infiltrometer (Matula and Kozáková 1997) and in the laboratory with the automated KSAT View device (METER Group, Inc.). The analysis of variance performed on log transformed *K(h)* data showed significant effect of applied pressure heads, but the differences between the CT, RT, and NT were not statistically significant probably due to very high *K(h)* data variations within the individual treatments. The highest *K(h)* values were determined for NT, then RT and the lowest for CT plot. That can be explained by the increased presence of mesopores being active within the applied pressure heads on NT and RT plots. On the other hand, the *Ks* values determined on NT plots were the lowest, then the RT and the highest values were determined on CT plot; documenting the importance of macropores in water movement in soil. Although the differences were clearly distinguished, they were not statistically significant. As a result, the null hypothesis has been accepted for this particular study area and time of measurement. The year 2018 was extremely dry and the soil conditions in the field were relatively difficult due to presence of big cracks and animal holes in the experimental area causing high variations of *K(h)* and *Ks* data within the individual treatments.

In addition to that, the *Ks* and *K(h)* values determined in 2018 were compared to data from 2015. Significantly higher *Ks* and *K(h)* values were determined for year 2018, confirming the effect of the very dry conditions in 2018. Also a significant effect of the applied type of the infiltrometer on the resulting *Ks* and *K(h)* data has been observed within this study.

Key words: saturated hydraulic conductivity, unsaturated hydraulic conductivity, tillage treatments, KSAT View Device, Mini Disk infiltrometer, Pressure infiltrometer

CONTENT

1 INTRODUCTION

Water is the principal determinant of vegetation distribution and one of the most limiting abiotic factors to the growth and development of plants. The importance of water to plants emanate from its role in photosynthesis and the distribution of nutrients and its movement through the soil profile which is facilitated by the soil hydraulic properties. Ali et al, (2014) classified hydraulic properties of soil into two categories; namely: water retention and water transmission properties. Water retention properties include saturation capacity, field capacity, wilting point, etc. Water transmission properties include permeability, hydraulic conductivity, and infiltration capacity. Out of all the soil hydraulic properties, hydraulic conductivity including saturated hydraulic conductivity *Ks* and unsaturated hydraulic conductivity *K(h)* is an important parameter (Zhuang et al., 2001). It describes the ease with which fluid especially water can move through pore spaces in the soil.

Tillage is one of the oldest management practices carried out on the field prior to planting as it helps to loosen the soil and aid the mixing of manure with soil. It involves cutting through the soil, upturning and loosening of the soil which could be done manually or mechanically. Tillage alters the structure of the topsoil layers and consequently their hydro-physical properties thus modifying the soil water regime (Moret and Arrúe, 2007). Soil hydraulic conductivity *Ks* and *K(h)* is very sensitive to compaction which is usually caused by wheels of machines used in the process of shearing, kneading, upturning and loosening of the soil. Hydraulic conductivity could also be influenced by various factors such as cracks, worm holes, root holes and stability of soil crumbs (van den Akker and Soane, 2005).

Since soil management influences physical properties and mainly the soil hydraulic functions, their measurement has become one of the research preferences in the branch of applied soil science (Angulo-Jaramillo et al., 2000). Different techniques have been developed and used for the measurement of *K(h)* such as tension infiltrometer (Zeng et al., 2012), pressure ring infiltrometer (Matula and Kozáková, 1997), constant water head permeameter (Osunbitan et al., 2005) as well as the estimation of soil hydraulic properties using pedotransfer functions (PTFs) Nemes et al. (2005) Therefore, the aim of this thesis is to evaluate saturated and near saturated soil hydraulic conductivity under different tillage treatments. It is expected that this paper will contribute to the ongoing research being conducted to understand and define the influence of tillage treatments on soil hydraulic conductivity.

2 HYPOTHESIS AND OBJECTIVES

Hypothesis

The following null hypothesis H_0 has been formulated and tested: There are no significant differences between the hydraulic conductivities of soil under no-tillage and tillage soil management practices.

Objectives

In order to verify the null hypothesis assuming no significant effect of soil treatment on the hydraulic conductivity of the soil, the following objectives were investigated in this study:

I. Determination of saturated and unsaturated hydraulic conductivities by own measurements on soil with different treatments (CT, RT, NT).

II. Evaluation of the data collected from field and laboratory measurements of saturated and unsaturated hydraulic conductivities for the same plots with CT, RT and NT from 2015.

III. Application of a suitable statistical tool enabling comparison of the resulting data in order to accept or refuse the null hypothesis formulated above.

3 LITERATURE REVIEW

3.1 SOIL HYDRAULIC CONDUCTIVITY

Soil hydraulic conductivity *(K)* is regarded as one of the most important hydrological properties of the soil. It can simply be described as the measure of how easily water can pass through soil with high values indicating permeable material through which water can pass easily and low values indicating that the material is less permeable. Soil hydraulic conductivity plays a major role in the effective use and management of water resources especially in agriculture where it is necessary to supply the plants as much water as it needs (Sari, 2017). Soil hydraulic conductivity typically varies by orders of magnitude in space and time. Hydraulic conductivity *K*-value in the soil profile can be highly variable from place to place and with variations at different depths, which means spatial variability. *K*-values can be variable not only in connection with different soil layers, but also within a one soil layer (Stibinger, 2014). The time variation in saturated hydraulic conductivity could be as a result of natural or artificial changes in soil structure (bulk density, porosity, pore sizes, pore connectivity, soil compaction, etc.). The variations are common in agricultural soils as some of the soil and water management practices as well as the wetting and drying cycles of the climate (Mubarak et al., 2009) have been identified as some of the sources of variability of soil hydraulic properties. Coquet et al. (2005) also showed in their research that tillage especially ploughing creates macro porosity that temporarily increases saturated and near- saturated *K*.

Bagarello et al. (2005) described hydraulic conductivity *(K)* as an important parameter for describing soil water flow, such as surface water infiltration and runoff, subsoil water recharge, and solution migration. This flow of water through soil was first quantified in 1856 by Henri Darcy because of his work carried out in the city of Dijon where he reported the filtration of water flowing through a saturated sand bed. Movement of water through the soil occurs under saturated and unsaturated conditions. The hydraulic conductivity of surface soil layers at and near saturation is an important parameter regulating the partitioning of precipitation between surface runoff and groundwater recharge, plant water uptake and plant growth, rates of biogeochemical cycling in soil and risks of pollutant impacts on surface waters and groundwater (Jarvis et al., 2013).

On one hand, unsaturated hydraulic conductivity measures the flow of water through the soil when some of the pores are filled water and others are filled with air. According to Perkins

(2011), unsaturated hydraulic conductivity is one of the main properties considered to govern the flow of water through the soil but considered to be very difficult to measure accurately. However, it is important when evaluating the movement of pesticides and nutrients through the soil at different water contents (AGVISE, 2018). On the other hand, saturated hydraulic conductivity is a quantitative measure of a saturated soil's ability to transmit water when subjected to a hydraulic gradient and could be regarded as the ease with which pores of a saturated soil permit water movement. It follows Darcy’s law which described it as the proportionality factor relating the volume of water passing through a cross-sectional area of the soil to the hydraulic gradient.

3.2 DETERMINATION AND FACTORS THAT INFLUENCE SOIL HYDRAULIC CONDUCTIVITY

Various techniques, models and equipment have been developed to aid the measurement and determination of soil hydraulic conductivity. Saturated hydraulic conductivity can be determined in the laboratory using constant head or falling head apparatus. The field (in-situ) measurement methods can be further divided methods measuring below the water table (saturated) and above the water table (unsaturated). Measurements below the water table can be determined by using the slug test and pumping test while above the water table is measured using constant-head well permeameter method and double cylinder infiltrometer (Amoozegar, 2009).

Mohsenipour and Shahid (2016) reviewed the existing methods used for the estimation of hydraulic conductivity and assessed the suitability of the methods used both in the lab and field. The results of their research showed that the constant head and falling head method used in the laboratory were suitable for measurement in soils with low hydraulic conductivity due to the inhomogeneity of the collected soil samples caused by the presence of wormholes, stones etc in samples. In addition, they stated that in situ measurement taken below the table level is more reliable as it allows the use of undisturbed and larger soil samples. However, the use of Auger-hole method below the water table was declared unsuitable for strongly layered soils or soils with irregular pore spaces distribution but most accurate for horizontal measurements. Piezometer method for water table level near to the soil surface was labelled accurate for measuring both horizontal and vertical hydraulic conductivity and estimating the impact of soil heterogeneity. Stibinger (2014) wrote that the determination of hydraulic conductivity soils can be realized with correlation methods or with hydraulic methods. He elaborated further by dividing hydraulic methods into laboratory or field methods while correlation methods come from predetermined relationship between soil property (e.g. grain size distribution, texture, etc.). However, the application of relationship can be incorrect and pose some random errors but advantageous as it ensures fast estimation over direct measurement. The hydraulic methods are derived from certain flow conditions, with boundary and initial conditions and uses Darcy's Law with equation of continuity. The laboratory methods are fast and cheap and used to core soil samples, but they have similar disadvantage as correlation methods and the small sample area means the high possibility of a large random error. Whereas, the hydraulic fields methods are based on description of the water flow processes and can measure K-values around the hole made in the investigated soils (in a case of small-scale). The hydraulic field methods can be divided into small-scale and large-scale methods, where small-scale field methods serve for fast testing of many locations, allowing the simplifications of groundwater (subsurface water) flow, so that measurements can be realized relatively cheaply and quickly. The large-scale field methods ensure the representative K-values, where the problem of variation is eliminated as much as possible, but it is expensive and time-consuming when compared with other methods. Figure 1 below shows a schematic representation of the hydraulic conductivity determination methods.

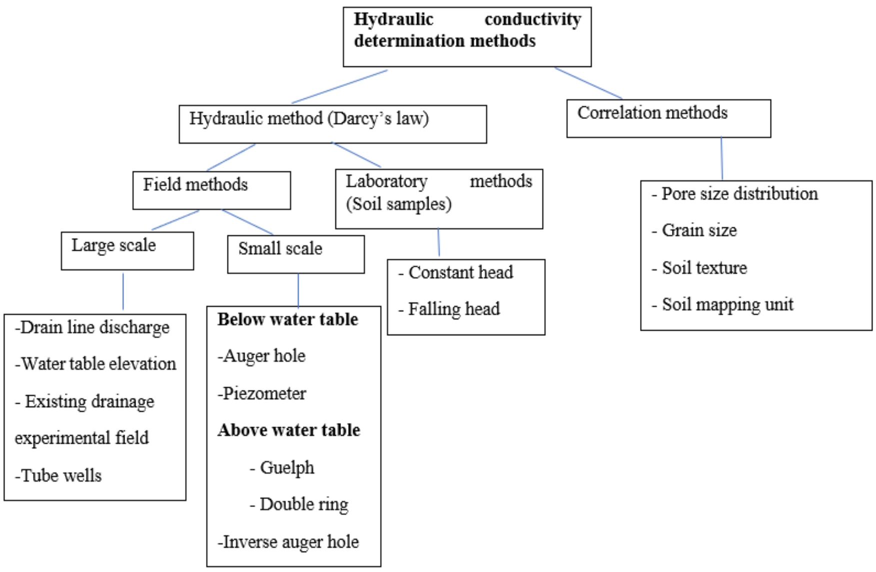


Figure 1: Overview of methods for the hydraulic conductivity determination (Source: Ritzema, 2006).

The use of infiltration-based methods such as the confined 1-dimensional pressure ring infiltrometer and unconfined 3- dimensional tension disc infiltrometer were regarded as valuable in the investigation of hydraulic and transport soil properties by Angulo-Jaramillo et al. (2000). This suitability was due to the portability of the tools which offers a simple and fast means of estimating soil hydraulic conductivity at the soil surfaces. The tools were also flawed as being associated with simplifying assumptions of the analysis used to infer soil hydraulic properties from water and solute flow. Also, that the weight of the infiltrometer ring may induce collapse of the soil and lead to negative values of hydraulic conductivity.

Measurement of hydraulic conductivity above the water table requires special equipment and techniques, of which some of them may be difficult to perform, time- consuming and may require a large volume of water to saturate the soil (Mohsenipour and Shahid, 2016). Perkins (2011) described the measurement of unsaturated hydraulic conductivity as costly and time-consuming which has encouraged the use of models to estimate it from more easily measured bulk-physical properties. To substantiate the use of models, she reported that the use of models such as Rosetta Pedo-transfer model or van Genuchten water retention model may produce about the same goodness of fit between the measured and modelled hydraulic conductivity data since numerical models of variably-saturated solute transport requires parameterized hydraulic properties as input. Although, the results of the models vary widely for a highly simple conceptual model and it is likely that the addition of more physically realistic characteristics would further affect the model performance in complex ways. Pedotransfer functions (PTFs) are mostly used when data on hydraulic conductivity is required for large areas. PTFs are predictive functions of certain soil properties using data from soil surveys. The most readily available data come from soil survey, such as field morphology, soil texture, structure and pH. Nemes et al. (2005) stated that the estimations using PTFs offers a competitive alternative to the time and cost intensive situations associated with direct measurements. Also, soil hydraulic PTFs are, in most cases, not specifically developed to address one problem, but are developed from a larger data collection to provide information to many studies.

Similarly, Zhuang et al (2001) proposed a new model for estimating unsaturated hydraulic conductivity by combining the Non-Similar Media Concept (NSMC) to the one parameter model of Brooks and Corey. Their results indicated that the NSMC based model could accurately predict unsaturated hydraulic as compared to four one-parameter models and van Genuchten -Mualem model. They concluded that estimation errors in a one-parameter model may arise due to the assumption that relative hydraulic conductivity depends solely on the water retention characteristics while other factors such as bulk density and specific surface area of soil may affect it as well. This makes the NSMC model superior to other models in predicting unsaturated hydraulic conductivity as it incorporates bulk density and parameters related to soil texture. Due to the impact of pore connectivity on hydraulic flow, a negligible estimation deviation for water retention characteristics may induce a significantly larger deviation in the estimation of unsaturated hydraulic conductivity. Therefore, they suggested that new theories or concepts that mechanically include a component of pore and particle arrangements be developed in the simulation of soil water flow.

Hydraulic conductivity is affected by both soil and fluid properties. It depends on the shape, size, distribution of the pores; viscosity and density of water geometry and soil temperature as well as the fluid viscosity and density (Mohsenipour and Shahid, 2016). The hydraulic conductivity for a given soil becomes lower when the fluid is more viscous than water. Jarvis et al. (2013) identified bulk density, land use and soil organic carbon content as the three most important predictors of saturated hydraulic conductivity. A significant effect of bulk density on saturated hydraulic conductivity, *Ks*, relates mostly to the effects of temporal variations in porosity in cultivated arable topsoil. Their research revealed that intensive agriculture reduces top soil and thus creates negative correlations between saturated hydraulic conductivity and soil organic carbon. Hati et al. (2007) found out that the aggregate stability was positively correlated with the soil organic carbon content. Not only do organic materials increase the water retention capacity in the soil but they also positively impact the soil structure.

Sari (2017) conducted a study to reveal the effects of different soil management applications together with soil's physical or chemical properties on its hydraulic conductivity. He examined various factors such as level of clay, sand, particle density, bulk density, silt, $CaCO_3$, pH, electrical conductivity (EC) and porosity. His results showed that the amounts of organic materials in the research soils had a positive effect on hydraulic conductivity values and increased the hydraulic conductivity of the soils but the increase in the hydraulic conductivity of the soils was statistically insignificant. Also, that organic materials increased the water retention capacity in the soil, but they also have a positive effect on the structure as the number of macropores increased, leading to an increase in hydraulic conductivity. The study showed that EC and pH values of the research soils had no significant effect on hydraulic conductivity and were statistically insignificant. Similar results were recorded by Yılmaz and Alagöz (2008) as they found that high amounts of organic materials in soils increase porosity, hydraulic conductivity and water retention capacity.

Hydraulic conductivity depends not only on total porosity but also on the sizes, shapes and connectivity of the conducting pores. This is obvious in the conductivity of sandy soils with large pores which is greater than the conductivity of a clay soil with narrow pores. In the study conducted by Wang et al (2009), they recorded a negative correlation between saturated hydraulic conductivity and soil carbon in sandy soils in a semiarid region. The relationship between K_S and soil carbon was found to be nonlinear as K_S becomes more sensitive to soil carbon at a soil carbon content less than 0.1%. They stated that the reduced wettability caused by the soil organic matter (SOM) is likely to be a reason for the observed negative correlation as it surpasses the impacts of an increase in saturated conductivity caused by soil aggregation. The presence of low soil organic matter content and large particle size of sand may also explain the limited effect of SOM on soil aggregation processes in the examined soils.

3.3 EFFECTS OF TILLAGE TREATMENT ON SOIL HYDRAULIC CONDUCTIVITY AND SOIL PROPERTIES

Since time immemorial, tillage has been a practice carried out to prepare the soil for planting. Whether manually or mechanically, it involves the preparation of lands prior to planting by digging, stirring, overturning and loosening the soil. This shows that tillage exerts an impact on the soil purposely to produce crops and consequently affects the environment (Busari et al, 2015). The tillage treatment of the top layer plays a key role in changes of the hydro-physical properties, mainly saturated hydraulic conductivity *(K)* of the treated layer (Matula, 2003). The degree of soil loosening and overturn by tillage depends on soil texture, soil moisture, organic matter, and type of tillage operation. Ali et al. (2014) described tillage practices as a process which alters the state of the soil from the initial state to a new state, with changes in the physical, chemical and biological environment of soil. It loosens the soil, changes its volume, and reduces bulk density while the compaction increases the bulk density. A decrease in bulk density increases the total porosity and the proportion of macro-pores, which in turn increases the soil's ability to hold water.

As discussed by Strudley et al. (2008), most tillage practices possess pronounced effects on soil hydraulic properties immediately following tillage application, but these effects can diminish rapidly. This indicates that the effects are temporal, and the affected properties could be subjected to soil consolidation effect, which can be observed in different times based on the soil type and crops sown.

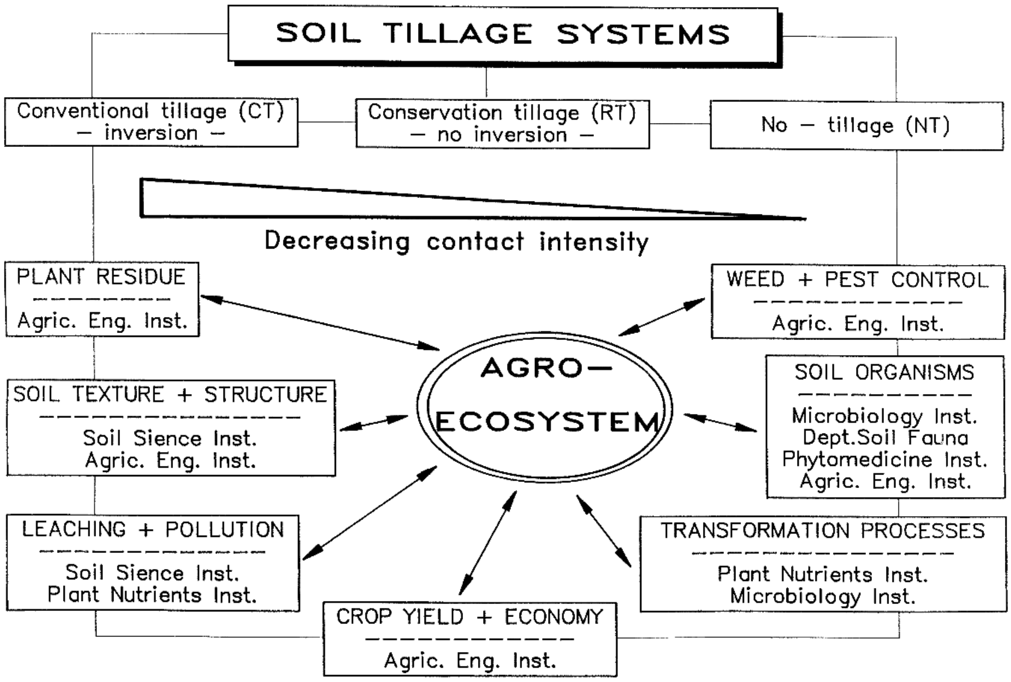


Figure 2: Institutes and research subjects involved in the joint project the interrelations of soil tillage systems and the soil ecosystem. Source: (Tebrugge and During, 1999).

Conventional tillage (CT) refers to the treatment of arable land which involves inversion of the soil, normally with a mouldboard or a disc plough as the primary tillage operation, followed by secondary tillage with a disc harrow. This leaves the soil exposed to rain and wind, which can sometimes lead to erosion of the topsoil.

Conservational tillage or Reduced tillage (RT) refers to the arable land treated by a non-inversion method which leaves plant residues on the soil surface for erosion control and moisture conservation. Planting in this way allows the crop residue to break down, which adds organic matter (like composting) to the soil.

Zero tillage or No tillage (NT) refers to the arable land on which no tillage is applied between harvest and sowing. Zero tillage is a no-tillage practice in which the crop is sown directly into the soil not tilled since the harvest of the previous crop. Weed control is achieved using herbicides and/or appropriate mulching and stubble is retained for erosion control.

Several studies have evaluated the effects of various tillage practices on the hydraulic properties of the soil. Physical properties of soil that may be affected by the loosening include bulk density, soil strength, infiltration capacity and water redistribution within the soil. Stable soil aggregates are crushed and macroporosity decreases when tillage is carried out especially on wet soils

(Matula, 2003). Understanding of soil pore geometry and structure is fundamental to the identification of tillage effects on soil physical and hydraulic properties. Strudley et al. (2008) reviewed tillage effects on soil hydraulic properties in space and time. They concluded that No-till (NT) would increase macropore connectivity while inducing no changes in porosity and bulk density when compared with conventional tillage. Likewise, Soracco et al (2012) itemized that for soils under NT it would be expected that traffic-induced compaction may be compensated by the progressive creation of macropores from roots and faunal activities with time, but this was not confirmed in their study. The lack of macropore formation under NT further laid credence to the idea that soil water movement occur mainly through the creation of water-conducting macropores.

Špongrová et al. (2010) conducted their experiment in four phases within approximately one-year period on the identical experimental field as in this study. Significant differences were recorded between NT, RT and NT management practices. The highest values of near-saturated hydraulic conductivity, *K(h)* were determined on CT plot, lower values on RT plot and the smallest values on NT plot. A significant increase in *K(h)* at the second experimental phase following the soil tillage operations was followed by a decrease in *K(h)* at the third and fourth measurement phase on CT and RT plots. On NT plot the *K(h)* values increased at the second and at the third experimental phase, then it decreased at the fourth stage. The vagaries in the measurements were conceived to be because of the improving effects of winter frost, wetting and drying periods and developing root system of the main crop that was present on the plot as at the time of the experiment.

In a recent study conducted by Jabro et al. (2016), zero tillage (ZT), shallow tillage (ST), and deep tillage (DT), ZT, ST and DT were the treatments implemented. Like NT, RT and CT, the soil was not tilled under ZT while for ST, the soil was tilled to a depth of 10cm and DT involved the tillage of the soil to a depth of 30cm. The study concluded that the soil treatments had insignificant effects on soil bulk density, saturated hydraulic conductivity and moisture content storage as the same values were maintained for total porosity in sandy loam soil under these three tillage practices. They maintained that soil texture was the main factor that determined total porosity in the soil thus affecting soil bulk density (BD), *Ks* and soil moisture content (MC) under each tillage practice used in their study. Their study showed large variations in *Ks* among ZT, ST and DT systems; however, these variations were not significant and inconsistent among three tillage treatments due to remarkable variability among replications within each tillage treatment. Osunbitan et al. (2005) observed a decrease in bulk density and penetration resistance of the surface soil as a result of an increase in the intensity of soil loosening. Saturated hydraulic conductivity reduced with the degree of soil manipulations during tillage due to the interruption of the continuity of macropores. However, bulk density and penetration resistance were recorded to have increased with time after the soil treatments as the soil gradually became compacted. They suggested that rainfall in combination with the cycles of wetting and drying of soil may have been responsible for the general increase in soil bulk density with time across the treatments in their study. Similar results were recorded in the study conducted by Fohrer et al. (1999) where wetting and drying cycles were found to have influenced the forming process of the surface seal, which caused the levelling and compaction of the surface and consequently affecting the hydraulic properties of the soil.

Although tillage assists in incorporating manure into the soil, controlling weeds, ensuring penetration of air into the soil and breaking up crusted soil and softening it for seed germination. Its impact causes disturbances to some soil physical properties. Soil is fractured during the process, structure is disrupted, and this may lead to the acceleration of surface runoff and soil erosion. Tillage also reduces crop residue, which helps to cushion the force of pounding raindrop. Various experiments and articles have been published documenting the effect of different tillage practices on soil hydraulic conductivity and other soil physical properties.

Considering the disadvantages that accompany the use of Conventional tillage, zero tillage or No-till presents an alternative which is becoming more widespread. It provides a way of growing crops from year to year without disturbing the soil through tillage. Its benefits include reduced fuel and labour requirements, reduced effect of water and wind erosion, increase in the amount of soil water and provision of a suitable environment for the soil organism. However, it may increase the usage of herbicide which could have a negative effect on the environment if used consistently for a long period of time. Overall, a clear understanding of the effect of tillage practices on soil hydraulic conductivity would help in the conservation and management of water resources to ensure a sustainable productivity.

4 MATERIALS AND METHODS

4.1 EXPERIMENTAL SITE

The field experiments were carried out at the Crop Research Institute located at Prague-Ruzyně (cultivated land area of 110 hectares; altitude 345 m above sea level; latitude 50°05'N; longitude 14°20'E; long-term annual precipitation 472 mm; annual average temperature 7.9°C).

According to the FAO system, the soil being tested is classified as Orthic Luvisol. A map of the location is displayed in Figure 3 below.

The experimental site was established in 1994 with three tillage practices on the same plot and this has remained the practice over the years. The three tillage practices were conventional tillage (CT) with the use of mouldboard plough up to the depth of 22 cm, reduced tillage (RT) with non-inversion treatment of top10 cm of soil and no-tillage (NT) with application of a direct drilling method.

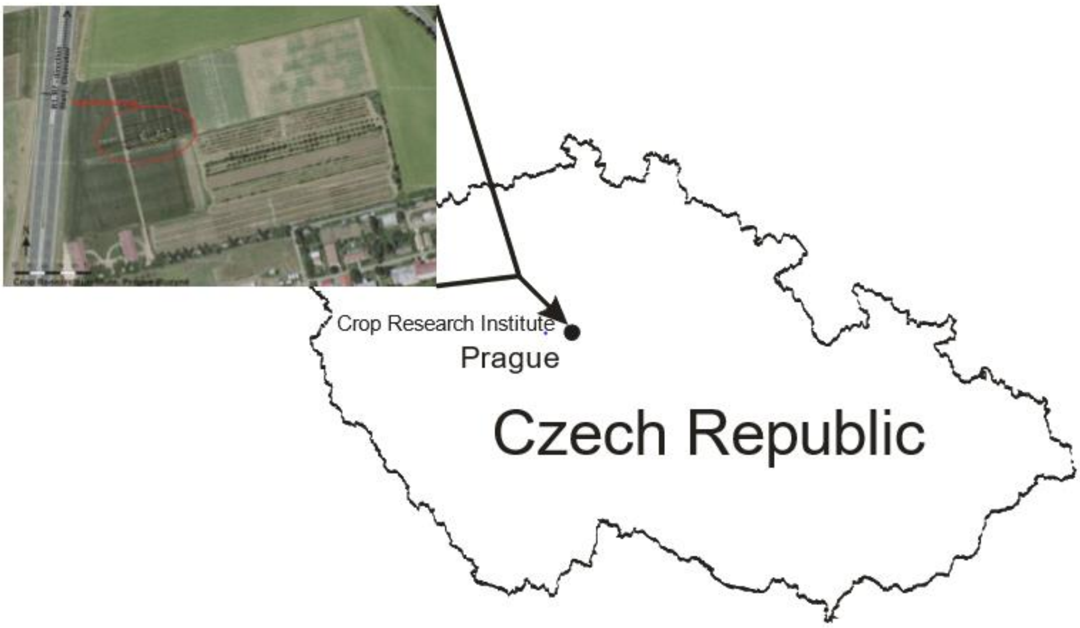


Figure 3. Location of the experimental site at Prague-Ruzyně (Source: Špongrová, 2010).

4.2 WEATHER CONDITIONS DURING DATA COLLECTION

At the time of the experiment in 2018, the weather was considerably warm and infiltration measurements were carried out on a dry soil. Figure 4 below shows the average daily temperature, maximum daily temperature and precipitation during the experiment. The days in which the experiments were conducted are also represented on the chart.

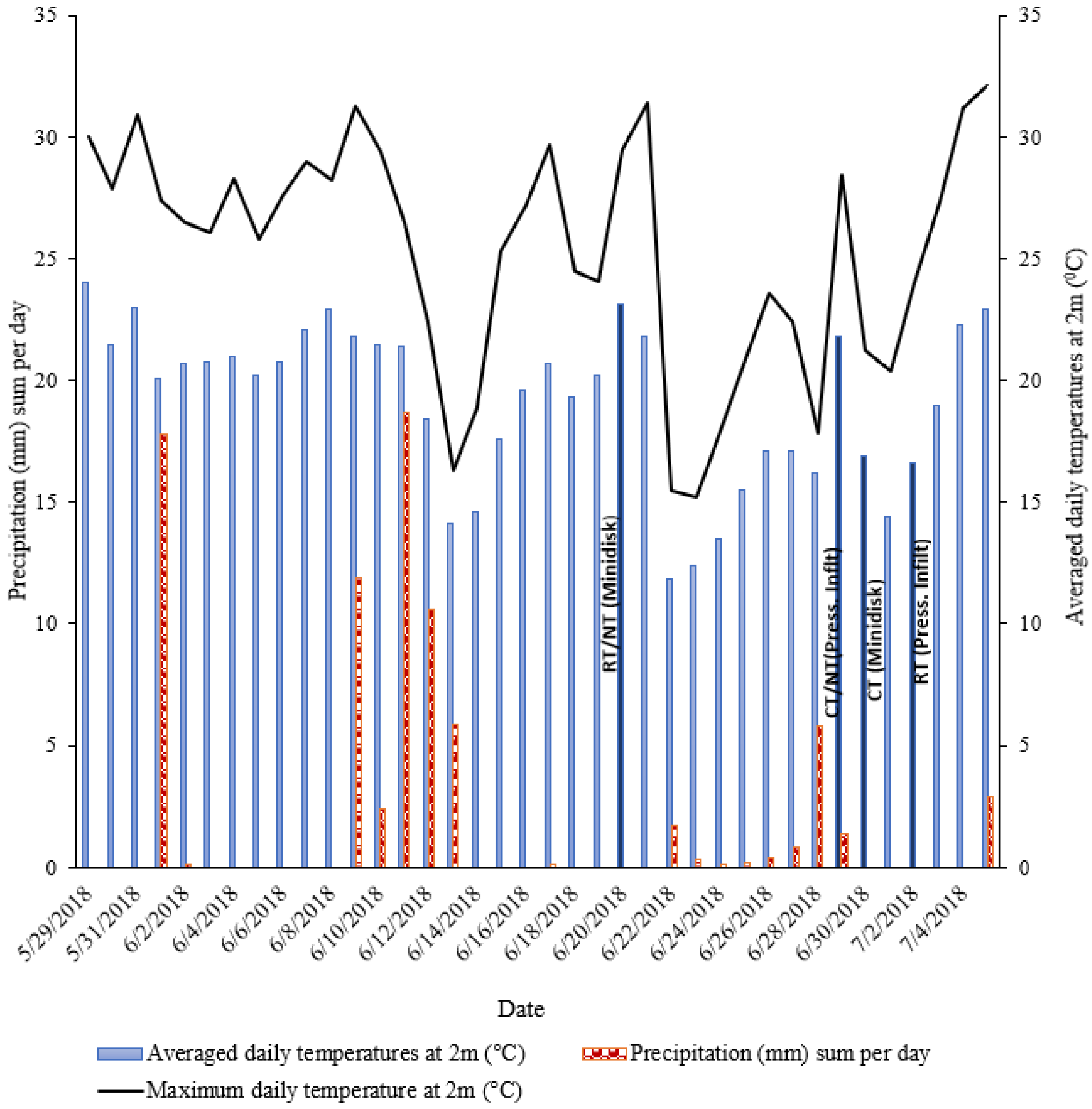


Figure 4. Weather condition during the field experiment in year 2018 (Data source: Agrometeorological station, Crop Research Institute Prague).

4.3 PHYSICAL AND HYDRAULIC PROPERTIES DETERMINED IN THE FIELD AND LABORATORY

At the time of the experiment, the main crop on the field was Wheat *(Triticum aestivum).* A total number of eight undisturbed samples were taken at the end of the experiment from the topsoil of each of the tillage treatment. Three samples each from RT and NT and two samples from CT were collected using 250 cm^3 stainless steel soil sample rings. The samples were taken to the laboratory for further analysis to determine the soil water content, dry bulk density and porosity and *Ks* using the KSAT device. .

Figure 5. Photograph of the field during experiment in July 2018.

4.3.1 Soil dry bulk density

Soil dry bulk density is an important characteristic of soil as it indicates the soil's ability to function for structural support, water and solute movement, and soil aeration. It is expressed as the dry weight of soil (g) divided by the total volume of soil (cm^3). It is mostly affected by compaction, soil depth, type of crops grown, seasonal variations and other factors which may disrupt soil structure. The undisturbed soil samples collected in a 250 cm^3 sampling rings were dried in the oven at 105^0C. The drying lasted for 24 hours as the sample had previously been saturated for saturated hydraulic conductivity measurements.

4.3.2 Soil total porosity

It simply refers to the number of pores present in the soil. Porosity is influenced by movement of roots, cracks, worms or small animals present on the field. Compaction caused by the wheels of machine could also limit soil porosity and affect its ability to transmit water. Porosity is calculated based on the values derived from particle density and soil dry bulk density. The values for particle density were obtained from a previous experiment conducted by Špongrová (2010).

4.3.3 Unsaturated soil hydraulic conductivity

Unsaturated hydraulic conductivity is considered to govern flow of water in the soil. It measures how water flows through the soil when the soil is not filled with water. Using the Tension infiltrometer method, infiltration rate can be measured at different water pressure heads. Although Perkins (2005) viewed the direct measurements of unsaturated hydraulic conductivity as expensive and time consuming, it is still widely used due to its portability and ability to characterize infiltration capacity of different pore classes (Špongrová et al., 2010). During the experiment, each of the measured data is recorded on an infiltrometer data sheet containing columns for time, square root of time, volume and infiltration. The data was then plotted using Microsoft Excel spreadsheet.

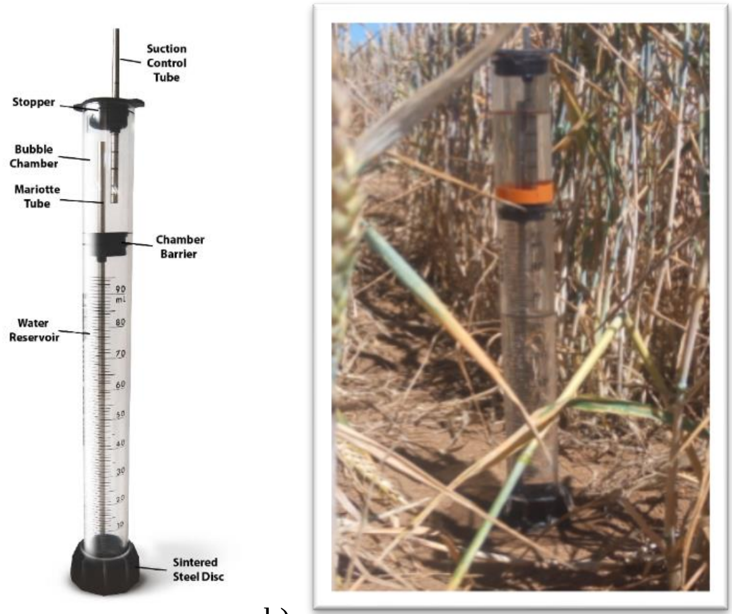
Mini Disk Infiltrometer (METER Group, Inc)

Unsaturated hydraulic conductivity was measured in the field with the aid of the Mini Disk infiltrometer. The infiltrometer consists of an upper chamber, lower chamber and a porous stainless-steel bottom. The two chambers are filled with water. The upper chamber controls the suction and the lower chamber which is marked like a graduated cylinder with volume shown in ml holds 95 cm^3 of water that infiltrates into the soil at a rate determined by the suction (pressure head between -0.5 cm to -6 cm) selected in the upper or bubble chamber. The bottom of the infiltrometer prevents water from leaking into the open air and the disk with a diameter of 4.5 cm and 0.3 cm allows for undisturbed measurements on relatively level soil surfaces. As the water level in the lower chamber drops and infiltrates the soil, the volume is recorded at specific time intervals. As stated in the User’s manual, the recommended time intervals for silt loam is 30 s and 30 to 60 min for tight clay (METER Group Inc., 2018).

Placement of Mini Disk infiltrometer during experiment

The lower chamber was filled to the 90 ml mark while the upper chamber was half-filled and pressure head was set at -5 cm. The infiltrometer was placed on a smooth and uniform soil surface to ensure a good contact between soil and infiltrometer. The stopwatch was started at the same time as the infiltrometer was placed on the surface with a time interval of 30 s. The time interval and volume were recorded accordingly on the infiltrometer data sheet. Based on the quantity of water that infiltrated after a certain time, the pressure head was adjusted to

-3 cm and lastly -1 cm. Three replicates were taken for each of the pressure heads and across all tillage treatments.



a) b)

Figure 6. Mini Disk Infiltrometer (a) Source: Mini Disk infiltrometer User´s manual (2018) (b) From field measurements.

A method proposed by Zhang (1997) was used to calculate for unsaturated hydraulic conductivity. The method was quite simple as it involved the plotting of cumulative infiltration against time and fitted using the equation below.

$$I = C_1 t + C_2 \sqrt{t} \qquad (1)$$

Where C_1 ($^{\alpha}$m/s) and C_2 (m/s$^{1/2}$) are parameters. C_1 is related to hydraulic conductivity, and C_2 is the soil sorptivity. The hydraulic conductivity K was then solved for using the equation below.

$$K = \frac{C_1}{A} \qquad (2)$$

Where C_1 is the slope of the curve of the cumulative infiltration vs the square root of time, and A is a value relating the van Genuchten parameters for 12 soil texture classes to the pressure head and radius of the Infiltrometer disk. Parameter A can be computed using the equations stated below or obtained from the table.

$$A = \frac{11.65(n^{0.1} - 1)\exp[2.95(n - 1.9)\alpha h]}{(\alpha r_d)^{0.91}} \qquad n \geq 1.9 \tag{3}$$

$$A = \frac{11.65(n^{0.1} - 1)\exp[7.5(n - 1.9)\alpha h]}{(\alpha r_d)^{0.91}} \qquad n < 1.9 \tag{4}$$

Table 1. van Genuchten parameters and values of *A* Mini Disk Infiltrometer (METER Group, Inc.); the soil being investigated is highlighted by the red box.

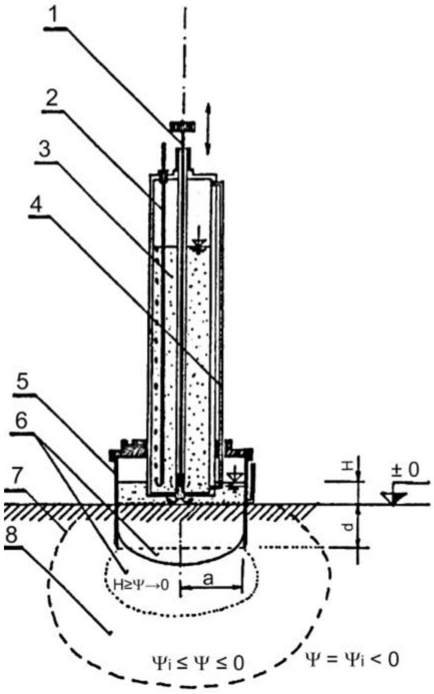
Texture	**α**	**n(h)**	**A** -0.5	-1	-2	-3	-4	-5	-6
Sand	0.145	2.68	2.9	2.5	1.8	3	0.9	0.7	0.5
Loamy sand	0.124	2.28	3.0	2.8	2.5	2.2	1.9	1.6	1.4
Sandy loam	0.075	1.89	4.0	4.0	4.0	4.0	4.0	4.1	4.1
Loam	0.036	1.56	5.6	5.8	6.4	7.0	7.7	8.4	9.2
Silt	0.016	1.37	8.1	8.3	8.9	9.5	10.1	10.8	11.5
Silt loam	0.020	1.41	7.2	7.5	8.1	8.7	9.4	10.1	10.9
Sandy clay loam	0.059	1.48	3.3	3.6	4.3	5.2	6.3	7.6	9.1
Clay loam	0.019	1.31	6.0	6.2	6.8	7.4	8.0	8.7	9.5
Silty clay loam	0.010	1.23	8.1	8.3	8.7	9.1	9.6	10.1	10.6
Sandy clay	0.027	1.23	3.4	3.6	4.2	4.8	5.5	6.3	7.2
Silty clay	0.005	1.09	6.2	6.3	6.5	6.7	6.9	7.1	7.3
Clay	0.008	1.09	4.1	4.2	4.4	4.6	4.8	5.1	5.3

Saturated hydraulic conductivity *Ks*

Saturated hydraulic conductivity can be described as the ease with which the pores in saturated soils permit the movement of water. Several methods exist to determine *Ks* both in the field (in-situ) and in the laboratory. The field measurements include the use of Pressure infiltrometer (Matula and Kozáková, 1997), Double ring infiltrometer (Parr and Bertrand, 1960), Guelph pressure infiltrometer (Reynolds et al., 1985) and Constant head pressure infiltrometer (Reynolds and Elrick, 1990). In the laboratory, constant and falling head apparatuses are commonly used on undisturbed soil samples collected from the field to determine the saturated hydraulic conductivity.

Pressure infiltrometer (Matula and Kozáková, 1997)

Previous experiments were conducted on the same experimental plot to determine saturated hydraulic conductivity also made use of Pressure infiltrometer by Matula and Kozáková (1997). The device is a Mariotte type infiltrometer constructed from non-corrosive materials (Plexiglas, PVC, Teflon) and uses a mechanical-hydraulic principle without the need for an external energy supply. The device allows for the measurement of *Ks* with acceptable accuracy cumulative infiltration of ponded water from a small infiltration ring. It consists of a metal infiltration ring (inner diameter of 15 cm) which is equipped by its own water gauge for reading of the constant water level *H* in the infiltration ring at a certain time after the start of the infiltration experiment. The depth of metal ring penetration into the soil can be up to 10 cm. Figure 7 below shows a schematic diagram of the Pressure infiltrometer with basic dimensions and its field application.

a) 

b) 

Figure 7. Pressure infiltrometer (Matula and Kozáková, 1997) a) 1- Piston valve to open or close the water outlet. 2- Moveable air tube to set the applied water pressure *H* on infiltrating surface. 3- Marriote type water reservoir. 4-Plexiglass tube of a small diameter to enable accurate fading of the water level. 5- Iron ring with a radius of a driven into the soil to the depth d. 6- Bulb of field saturated soil 7- Wetting front 8-Wetted zone. b) Field application.

Placement of the Pressure infiltrometer during experiment

A small path was cleared to remove plants and the metal ring was driven into the soil with a hammer. The ring was gently hammered into the soil so as not to disturb the soil and the infiltrometer was placed on the ring and filled with water. The closing valve was opened, and time needed for constant level was recorded using a stopwatch. The water level drop was monitored and recorded accordingly in selected time interval usually between 1 and 4minutes. 5 replicates were conducted for each of the tillage treatments and the experiment was concluded as the readings started to indicate steady-state flow.

Equations formulated by Philip (1985), Reynolds and Elrick (1990) and Elrick and Reynolds (1991) were applied on the steady-state infiltration data in order to determine *Ks*. The final equation is stated below (Eq. 5):

$$Ks = \frac{Q_{ti}\ G_{ti}}{\left(a\,H + a^2\,G\,\pi + \dfrac{a}{\alpha}\right)} \tag{5}$$

where Q_{ti} is the steady infiltration ($L^3\ T^{-1}$), a is radius of the infiltration ring *(L)*, G_{ti} is the shape factor ($L^3\ T^{-1}$), H is the hydraulic head of ponded water in the infiltration ring *(L)*, α is a parameter (L^{-1})(Philip, 1985 and 1987; for pressure infiltrometer details can be found in Elrick and Reynolds, 1989), K is the saturated hydraulic conductivity $(L\ T^{-1})$.

To use equation (5) above, G_{ti} and Q_{ti} were determined using the equations below and thereafter the values were fitted into the final equation in (Eq. 5).

$$G_{ti} = 0.316\left(\frac{d}{a}\right) + 0.184 \tag{6}$$

$$Q_{ti} = \frac{V_{cal}\ 1cm\ h}{\Delta t} \tag{7}$$

where d is the penetration depth of the infiltration ring into the soil *(L)* and a is the radius of the infiltration ring *(L)*, and h is the water level drop in the infiltrometer reservoir after the elapsed time interval Δt.

KSAT View Device using the falling head method (UMS GmbH, 2012)

This method is used in the laboratory to determine saturated hydraulic conductivity of undisturbed soil samples. Stibinger (2014) reported the method as a fast, cheap and suitable means of determining *Ks*; especially for layers with a low hydraulic conductivity, in horizontal or vertical direction. It measures for both fine-grained and coarse-grained soils and allows water to flow through the soil without maintaining a constant pressure head. However, a relatively small sample volume (usually 100 cm^3 or 250 cm^3) means the high possibility of a large random error.

Preparation of samples and placement of KSAT View Device during measurements

Each sampling ring was placed on a ring with a porous plate (lined with filter paper) and arranged on a raised platform in a trough. Water was added gradually to avoid flooding or trapping air in the samples. The samples were saturated for approximately 24 hours as recommended in the operation manual. Prior to the measurements, the KSAT View software had been installed on a computer and was connected to the device through a cable.

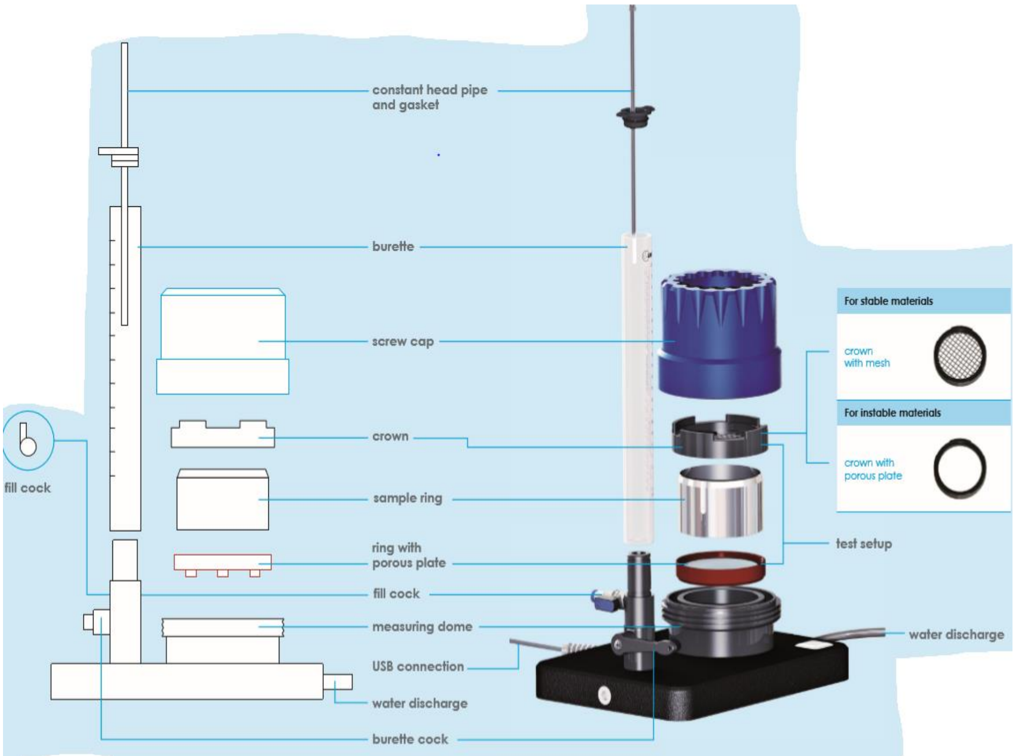


Figure 8. Diagram showing the various parts of the Device (KSAT VIEW, UMS GmbH).

The sample to be measured was transferred into another trough filled with water and the porous ring was gently removed The membrane protecting the soil surface of the top of the soil sample was replaced by the ring with the porous plate and the membrane from the bottom of the sample (cutting edge of the ring) was replaced by metal crown with the mesh (Figure 8). The fill cock was opened, the burette was filled to the 5 cm mark and fill cock was closed again.

Then the burette cock was opened to flood the measuring dome and closed afterwards. The sample was gently mounted and slightly tilted on the measuring dome to allow air escape. The crown was gently screwed on to the sample and the burette cock was opened to allow flow of water through the sample. This was done at the same time as the start measuring mode "falling head" in the software.

The water flows initially with high pressure and a correspondingly high rate, then at a progressively decreasing rate through the soil sample. The software automatically realizes the beginning of the pressure drop and sets this point of time as the starting point for computing.

The logged data were displayed graphically and as soon as at least 2 valid data were available *Ks* was computed in real time.

a) b) c) d) e)

Figure 9. Photo-documentation of the KSAT measurement a) Samples before saturation b) Samples during saturation c) Fittings before measurement d) After fittings and before transferring to the measuring dome e) Complete set-up during measurement.

The device uses the length of the soil sample (cm), area of the soil sample (cm²) and burette area (cm²) to compute *Ks*. The device measures the pressure head *H* (cm) depending on the time *t* (d). KSAT View uses the method stated in Equation 8. below to evaluate *Ks:*

$$Ks = \frac{A_{bur}}{A_{sample} \quad L \quad b} \tag{8}$$

where A_{bur} (cm^2) is the cross-sectional area of the burette, A_{sample} (cm^2) is the cross-sectional area of the sample, L (cm) is the length of soil sample and fitting an exponential function to the observed time series determines the coefficient b.

4.3.4 Soil water content

Soil water content defines the amount of water present in the soil. In agriculture, water content plays an important role because if available at optimum level, plants can readily use it for growth and development. Volumetric water content was determined based on the values derived from the mass of saturated soil sample and mass of dry sample and dry bulk density of the soil. Devices based on various principles are available to provide the in-situ measurement of soil water content. Such devices are i.e. Neutron probe method, Gamma radiation method and Capacitance method. Theta Probe soil moisture sensor was used in this experiment to measure all in-situ soil water content.

Theta Probe ML2x (Delta-T Devices Ltd; Cambridge UK)

Theta probe measures the volumetric water content based on electrical capacitance of a capacitor that uses the soil as a dielectric constant due to changes in soil water content. These changes are then converted into voltage which is proportional to volumetric water content. Theta Probe ML2x in combination with the HH2 Moisture Meter as a readout unit has been used. Soil specific calibration determined in previous research of Špongrová (2010) was set for the soil under investigation to get more accurate data. It was used at the beginning of each experiment to determine initial water content and final water content after each experiment with at least 3 replicates.

4.4 STATISTICAL ANALYSIS

Statistical evaluation of the results was carried out using a statistical software Statgraphics Centurion XV (Statpoint Technologies, Inc.). Analysis of variance was used to obtain statistically significant effects of different tillage treatments on soil hydraulic conductivity. The saturated and unsaturated hydraulic conductivity data were log-transformed (logarithm to the base of 10) in order to obtain normal distribution of the data. Fisher's least significant difference was used to discriminate among the means and significance level of 0.05 was considered for all the tests. Additionally, Variance component analysis has been applied on log-transformed *Ks* data from 2018 in order to estimate the contribution of each of the tested factor to the total variability of the given model.

5 RESULTS

5.1 SOIL DRY BULK DENSITY, SOIL POROSITY AND SOIL WATER CONTENT

The values for dry bulk density of soils obtained from each of the tillage treatments are represented in figure 10. The values were obtained from 2 or 3 replicates collected during the experiment.

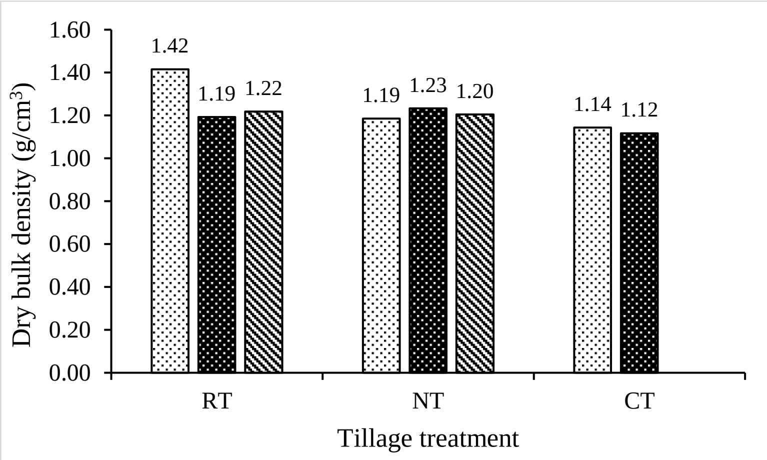


Figure 10. Dry bulk densities obtained for each of the tillage treatments in year 2018.

The results for soil porosity are represented in Figure 11. Saturated volumetric water content was determined and is shown in Figure 12. Like soil dry bulk density, the values obtained from 2 or 3 replicates were represented in the charts for soil porosity and saturated volumetric water content.

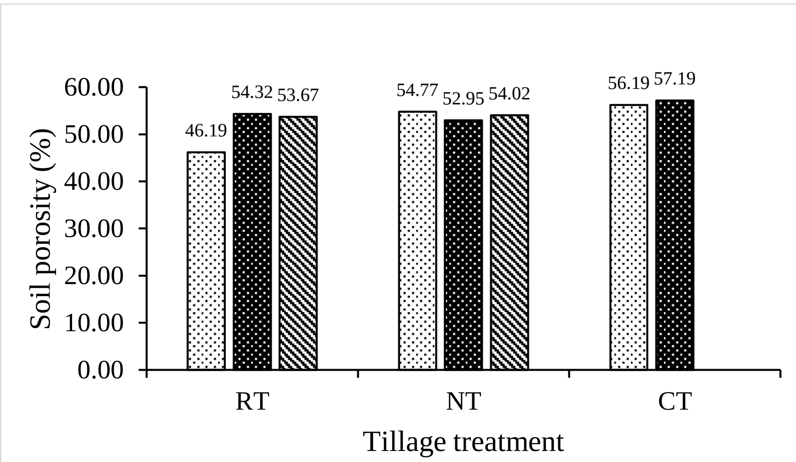


Figure 11. Soil porosity values obtained for each of the tillage treatments in year 2018.

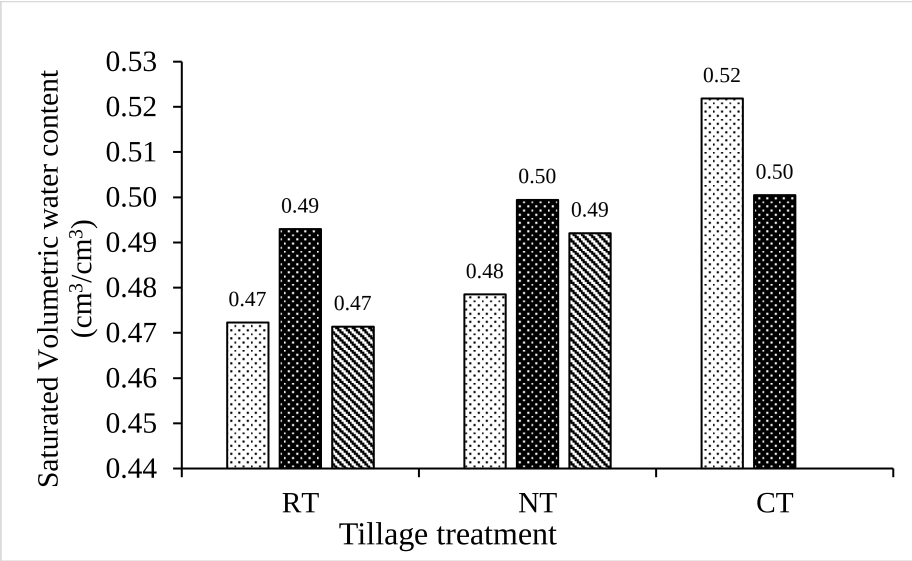


Figure 12. Values of saturated volumetric water content(cm^3/cm^3) obtained after saturation of the soil samples in the laboratory in 2018.

5.2 UNSATURATED HYDRAULIC CONDUCTIVITY *K(H)*

Mini Disk infiltrometer was used in the determination of unsaturated hydraulic conductivity. At pressure heads -5, -3 and -1cm respectively, 3 replicates were measured for each of the tillage treatments. The effect of soil treatment and tension applied were evaluated by the analysis of variance for log-transformed *K(h)* values.

5.2.1 *K(h)* measured by Mini Disk Infiltrometer

Based on the information available in the User's manual, the hydraulic conductivity was determined and the averaged values for each of the tillage treatments at various pressure heads were calculated and plotted in the chart below (Figure 13).

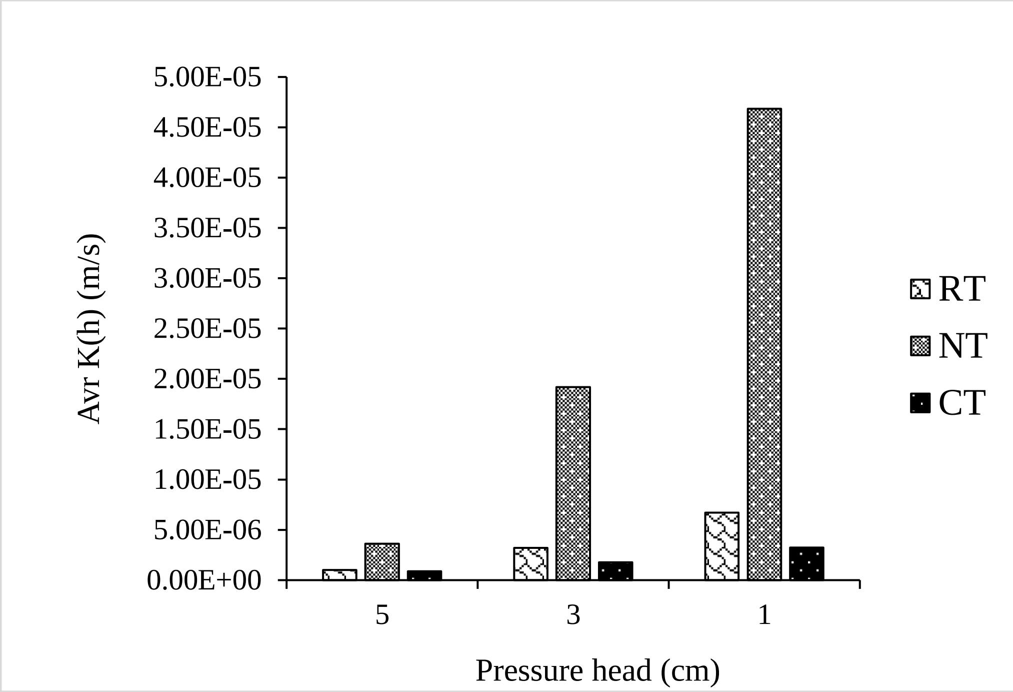


Figure 13. The averaged values of *K(h)* vs pressure heads for each of tillage treatments by Mini Disk infiltrometer in 2018.

The result of Analysis of variance for Log *K(h)* using the soil treatment as the 1st factor is displayed in Figure 14.

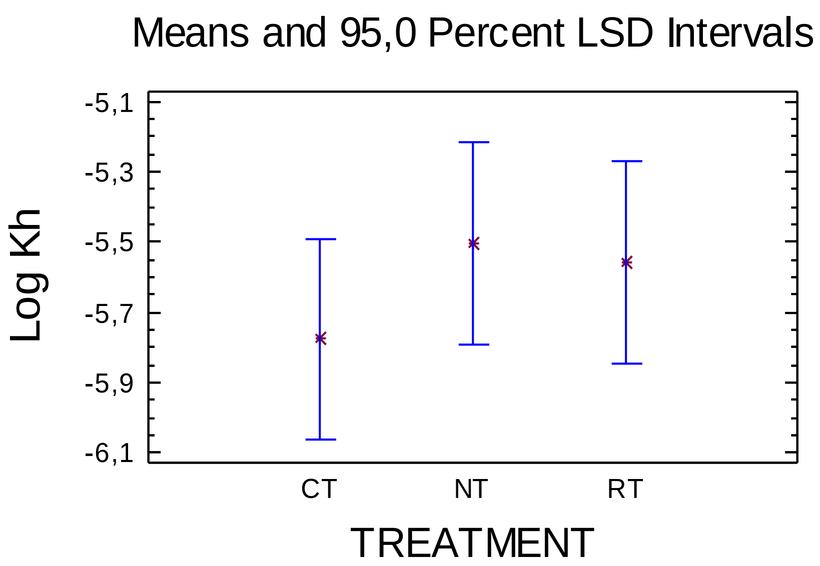


Figure 14. Analysis of variance showing insignificant differences in *K(h)* values for each of the soil treatment plot measured by Mini Disk infiltrometer in 2018.

The results obtained showed that due to a very high variability of *K(h)* values within each particular plot, no significant differences were observed on the basis of the Fisher´s LSD test for the Log*K(h)* values from the CT, NT and RT plots measured by Mini Disk infiltrometer at pressure heads -5.-3 and -1cm.

The result of Analysis of variance to determine if there are any interactions in Log *K(h)* values for each of the soil treatment under each applied tension is shown in Figure 15 and no statistically significant difference was observed.

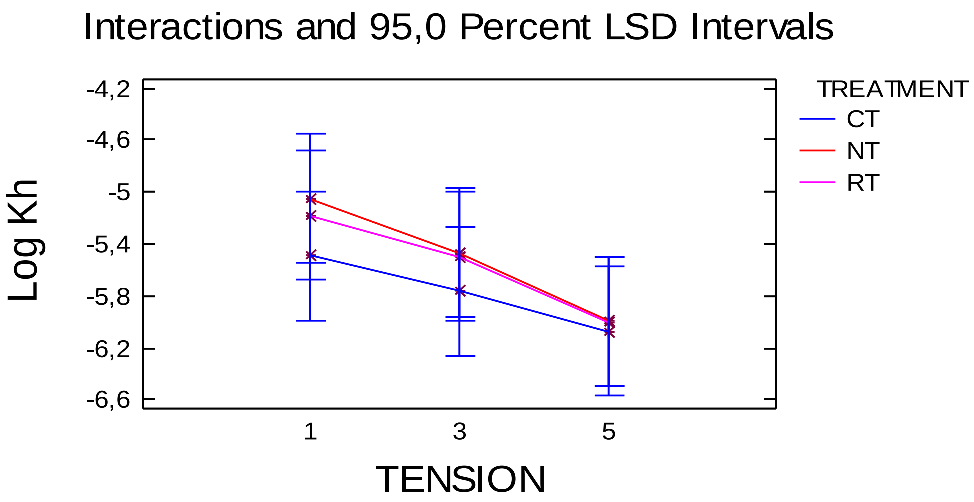


Figure 15. Analysis of variance results identifying interactions in Log *K(h*) values for each soil treatment under the three tensions applied determined by Mini Disk infiltrometer in 2018.

Alternatively, Analysis of variance for Log *k(h)* was carried out using the applied tension (pressure heads) as the 1st factor. Similar results were obtained as no statistically significant differences were observed. The graphical representation of the result is displayed below (Figure 16).

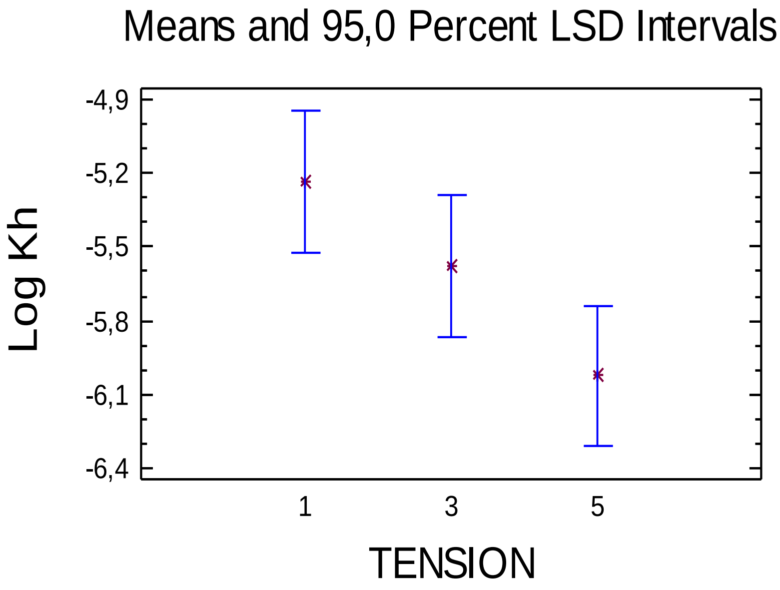


Figure 16. Analysis of variance showing insignificant differences in *K(h)* values for each of the tension applied by Mini Disk infiltrometer in 2018.

However, a multiple comparison procedure for Log *K(h)* by tension for each of the soil treatment showed a statistically significant difference between the pair of -1 and -5cm indicating a presence of macropores being active close to saturation The result is shown in the graph below (Figure 17):

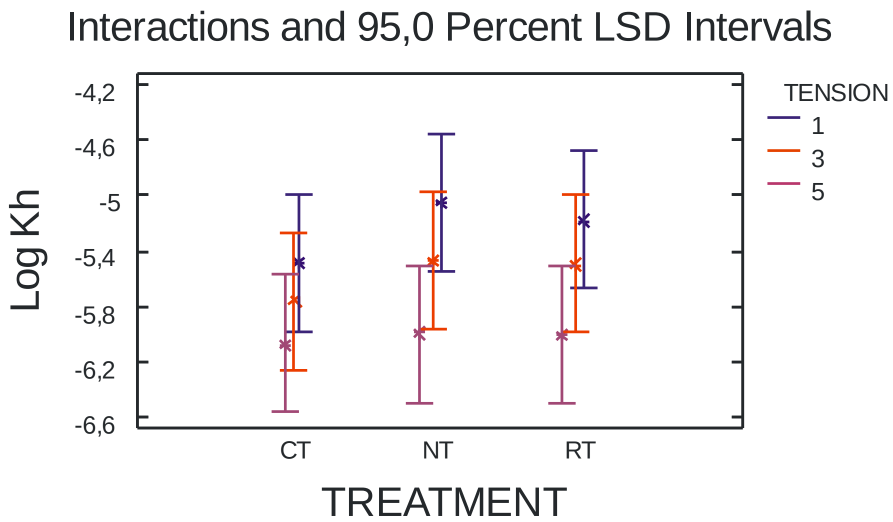


Figure 17. Analysis of variance results showing the difference in Log *K(h)* values for each of the tensions applied under each soil treatments measured by Mini Disk infiltrometer in 2018.

5.3 SATURATED HYDRAULIC CONDUCTIVITY *KS*

Data on saturated hydraulic conductivity were obtained based on measurements from Pressure infiltrometer (Matula and Kozáková, 1997) and KSAT View device (UMS GmbH, 2012). Data obtained with the use of Mini Disk infiltrometer were also extrapolated in order to estimate the values of saturated hydraulic conductivity.

5.3.1 <u>Data obtained with the use of Pressure infiltrometer (Matula and Kozáková, 1997) in 2018</u>

Five replicates were measured on each of the soil treatment during the experiment. The resulting *Ks* values for each of the tillage treatment are represented graphically in Figure 18. An averaged *Ks* value of 1.09E-04 m/s was obtained under CT, 7.18E-05 m/s for RT and 3.72E-05 m/s for NT. This showed that CT plot has the highest *Ks* value, followed by RT and the lowest was recorded for NT.

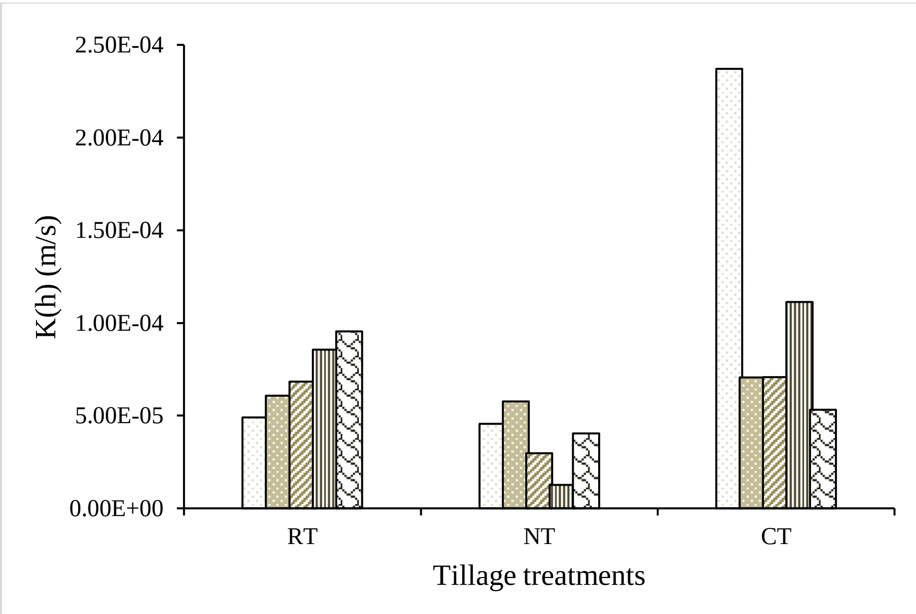


Figure 18. Graphical representation of *Ks* values measured with Pressure infiltrometer for individual replicates (Matula and Kozáková, 1997) in 2018.

5.3.2 <u>Data obtained with the use of KSAT View Device (UMS GmbH, 2012) in 2018</u>

Between 5 to 20 replicates were measured with KSAT View device as some of the samples had visible large pores, stones, cracks and roots which caused the infiltration to be fast and had to be repeated to get enough and good measurements. The averaged values are represented in

Figure 19. Like the measurements obtained with the Pressure infiltrometer, the highest *Ks* value was recorded for CT which bore a slight difference to RT values and greatly differs from the NT values.

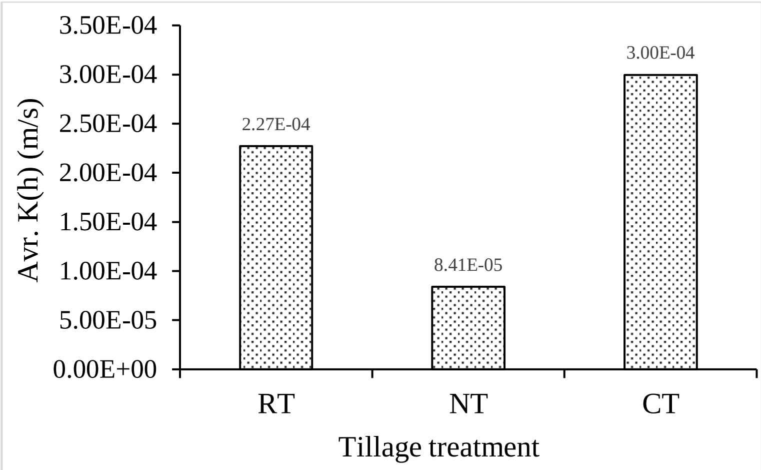


Figure 19. Averaged values of replicates determined by the KSAT View Device (UMS GmbH, 2012 now METER group, Inc.) in 2018.

Variance component analysis for Log *K(h)* was conducted in order to estimate the amount of variability contributed by each of the factor. The factors in this case were infiltration type (type of the device used for the infiltration experiment) and soil treatment. The result of the analysis showed that the infiltration type was responsible for 70.34% of the variations in Log *K(h)* values while soil treatment contributed 5.14% and the rest were errors (24.52%) detected.

The resulting *Ks* values obtained by different devices have reached different levels; the order was as follows: KSAT > Pressure infiltrometer > Mini Disk. At 95% confidence level, analysis of variance revealed a statistically significant relationship between the Log *Ks* values and the infiltration type used. While almost no significant differences were observed for *Ks* on different soil treatments measured by each of the infiltrometer type individually.

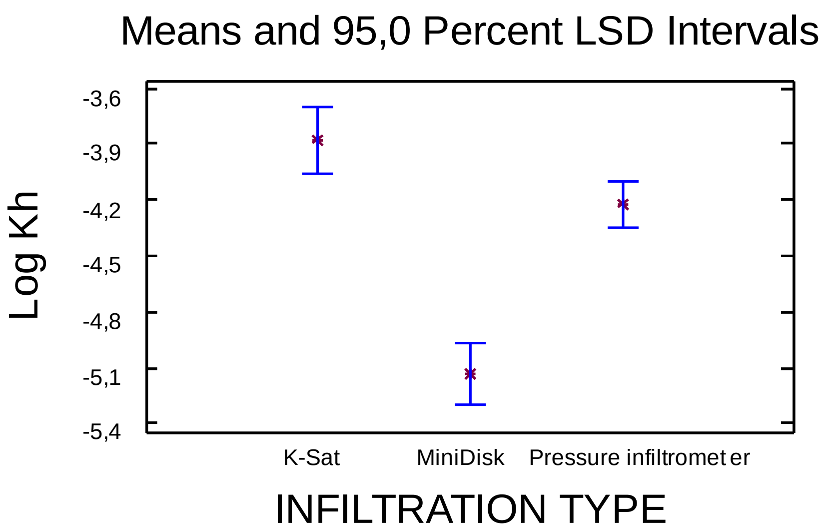


Figure 20: Analysis of variance showing the statistically significant differences in Log *Ks* values between the infiltration type used during measurements in 2018.

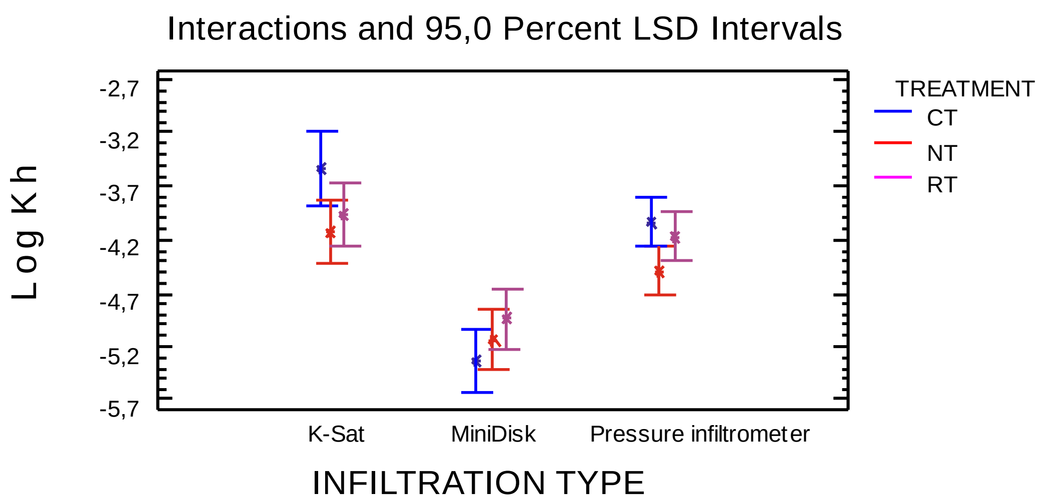


Figure 21. Analysis of variance showing the significant differences in Log *Ks* values determined by different infiltration type for each soil treatment in 2018.

5.4 COMPARISON BETWEEN THE DATA COLLECTED IN 2015 AND 2018

In order to have a better understanding of the complexity of the hydraulic conductivity matter, the time factor was also considered including comparison of own data to those measured in 2015. The data were measured on the same experimental site on all three tested soil treatments by employing the Mini Disk infiltrometer and Pressure infiltrometer (Matula and Kozáková, 1997).

5.4.1 *K(h)* values measured by Mini Disk infiltrometer in 2015

Based on the information obtained, measurements were taken at pressure heads -5cm and -1cm only as the soil was wet due to the incidence of rainfall prior and during the measurements. Based on the infiltration data records provided by the Department of Water Resources (CULS, Prague), the same data analysis as for data from 2018 was applied and the resulting averaged values of *K(h)* are presented in Figure 22.

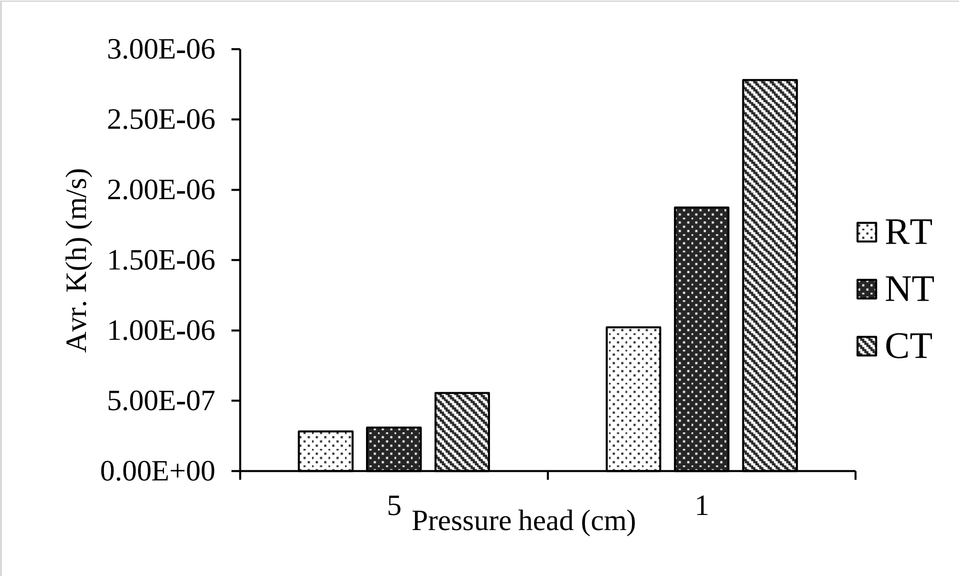


Figure 22. The averaged values of *K(h)* vs. pressure heads for each of tillage treatments by Mini Disk infiltrometer in year 2015.

5.4.2 *Ks* values measured by Pressure infiltrometer (Matula and Kozáková, 1997) in year 2015

Based on the infiltration data records provided by the Department, the data were analysed by the same procedure as in 2018 in order to get the *Ks* values from 2015 for comparison. The results of the 5 replicates measured for each of the soil treatment in year 2015 is shown in Figure 23. The averaged *Ks* values showed that NT has the highest *Ks* values with 9.33E-05 m/s, followed by RT with 4.88E-05 m/s and CT with the lowest value of 2.09E-05 m/s. The averaged result of NT was highly affected by one measurement reaching the highest value of *Ks* determined on NT plot ever. This value was also identified by the statistical analysis as an outlier affecting the whole analysis. Based on that, this particular measurement was removed from the input data being evaluated by the statistical software in order to compare results from years 2015 and 2018. This comparison is shown in Figure 24.

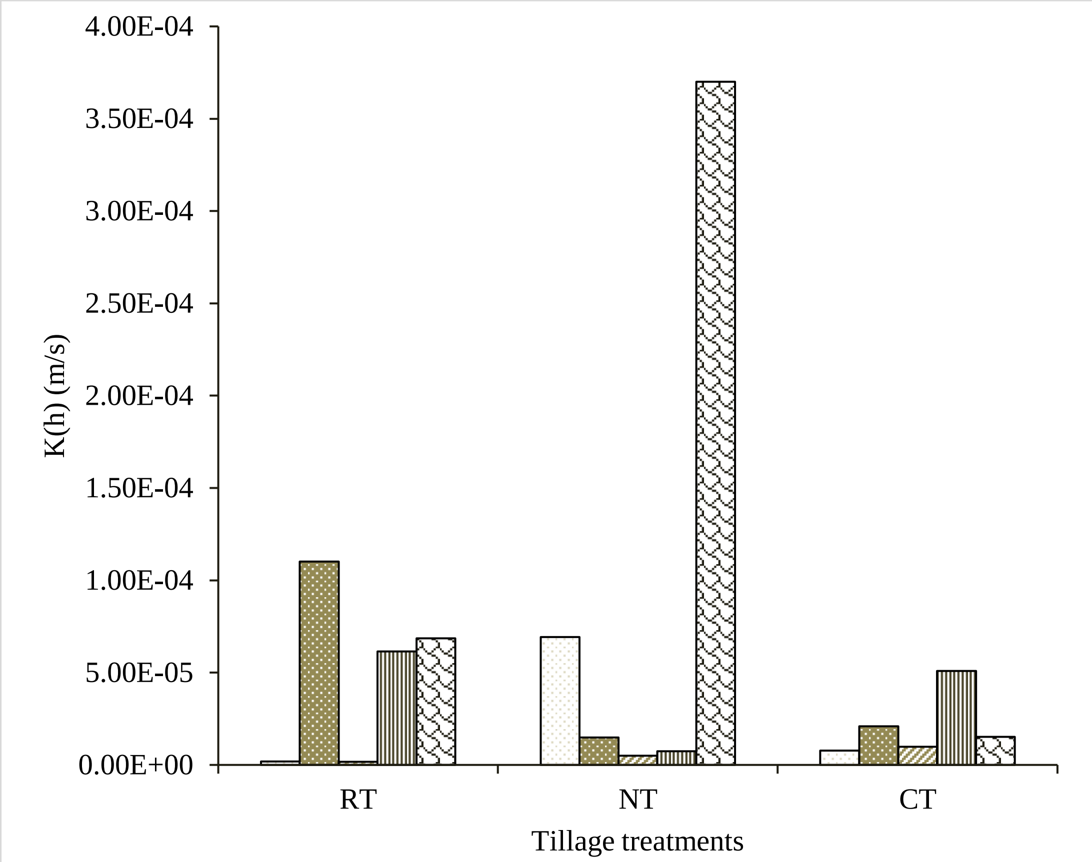


Figure 23. Graphical representation of *Ks* values measured with Pressure infiltrometer (Matula and Kozáková, 1997) for the individual replicates in the year 2015.

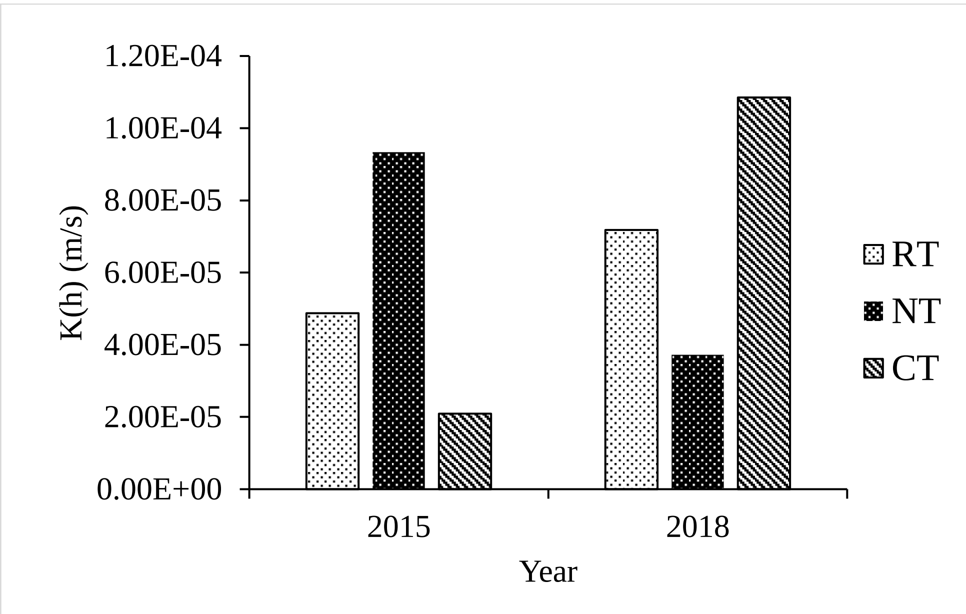


Figure 24. Comparison of the averaged *Ks* values measured by Pressure infiltrometer (Matula and Kozáková, 1997) for each of the soil treatments in years 2015 and 2018.

Analysis of variance (ANOVA) detected a significant difference in the multiple comparison procedure for log *K(h)* by year. This could be as a result of different soil conditions present in the field in the year 2015 and 2018 coupled with the differences in the initial soil moisture content.

Table 2. ANOVA results of multiple comparison procedure for *log K(h)* by year.

YEAR	*Count*	*LS Mean*	*LS Sigma*	*Homogeneous Groups*
2015	14	-6.33265	0.184737	X
2018	27	-5.61348	0.117915	X
Contrast	*Sig*	*Difference*	*+/- Limits*	
2015 - 2018	*	-0.719168	0.444923	

* denotes a statistically significant difference

This significant difference was observed for multiple comparison procedure for log *K(h)* by tension applied by Mini Disk infiltrometer for each of the soil treatment in years 2015 and 2018.

Table 3. ANOVA results of multiple comparison procedure for *log K(h)* by tension.

TENSION	*Count*	*LS Mean*	*LS Sigma*	*Homogeneous Groups*
5	16	-6,22083	0,154076	X
3	9	-5,93781	0,231775	XX
1	16	-5,76056	0,154076	X
Contrast	*Sig.*	*Difference*	*+/- Limits*	
1 - 3		0,177243	0,553366	
1 - 5	*	0,460272	0,43977	
3 - 5		0,283029	0,553366	

* denotes a statistically significant difference

However, the ANOVA results for the interactions of log*K(h)* values between each of the soil treatments measured in years 2015 and 2018 yielded significant differences between the RT and NT treatments showing consistently higher values of *K(h)* determined in 2018.

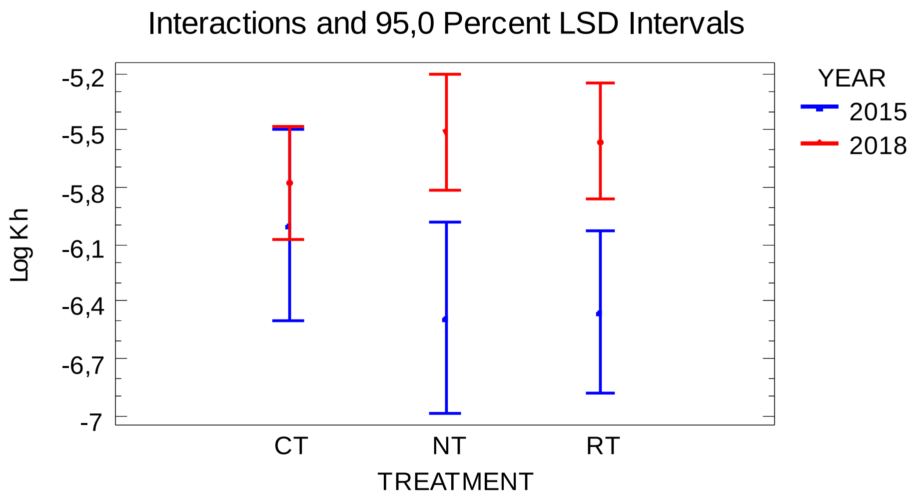


Figure 25. Interactions between the Log *K(h)* values obtained from each of the soil treatments by Mini Disk infiltrometer in the years 2015 and 2018.

For comparison between the *Ks* data obtained in 2015 and 2018, data determined by Pressure infiltrometer and values extrapolated from Mini Disk infiltrometer were used in ANOVA. The results observed showed that a significant difference existed between the infiltration type.

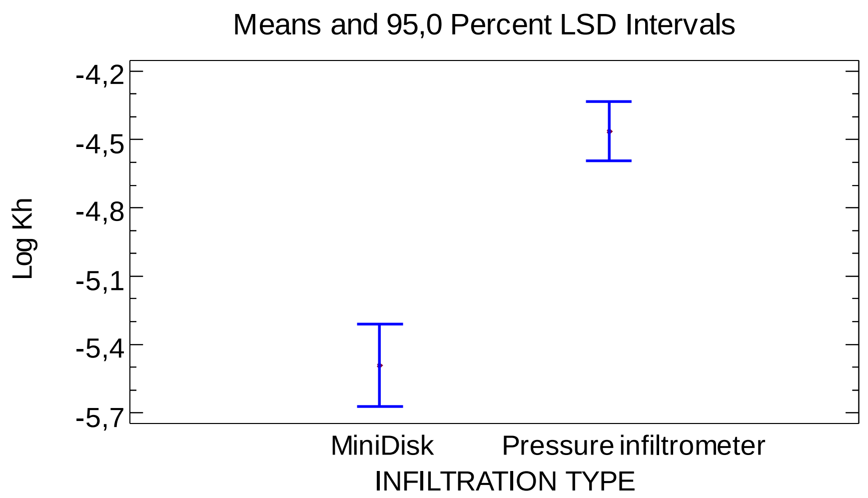


Figure 26. ANOVA recorded a significant difference in Log *K(h)* values between the infiltration type used for measurements of saturated hydraulic conductivity.

More interesting is the comparison of the *Ks* results obtained for the years 2015 and 2018 (Figure 27) following the trend set-up by the data from the Mini Disk infiltrometer and showing significantly higher *Ks* values for year 2018.

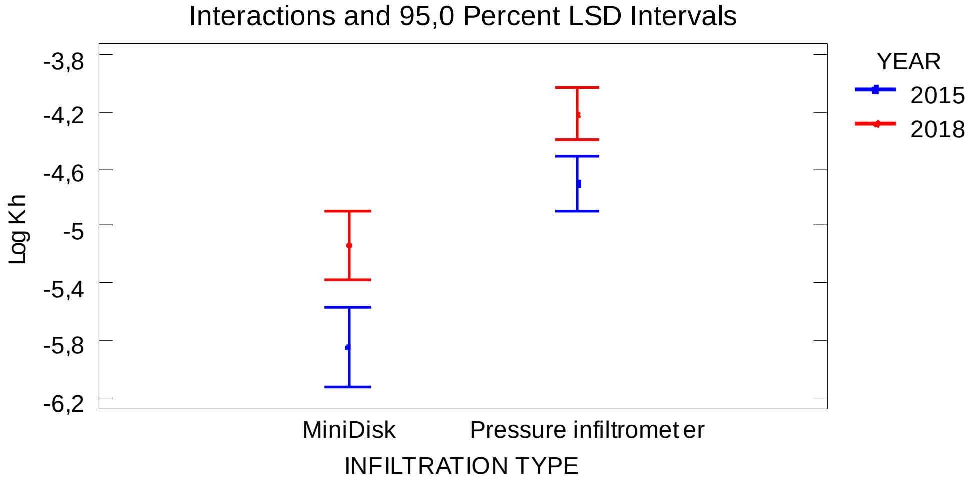


Figure 27. Significant differences depicted by ANOVA in the Log *Ks* values obtained by the infiltration types used in the years 2015 and 2018

Relatively variable *Ks* values were observed during the years 2015 and 2018, so no significant differences have been identified between the CT, RT and NT (Figure 28). However, significantly higher values of *Ks* were determined in 2018 (Figure 28, and Table 4).

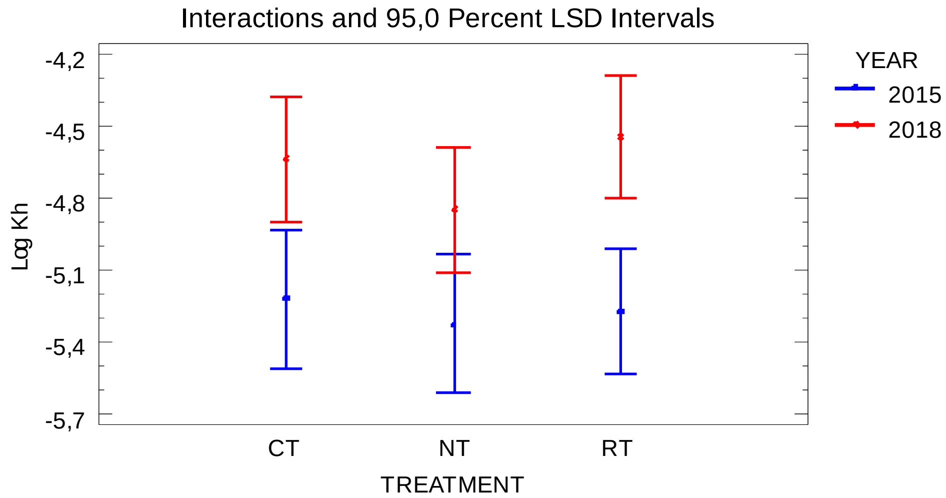


Figure 28. No significant difference in Log *Ks* values obtained for each of the soil treatments in years 2015 and 2018.

Table 4 represents the result of multiple comparison procedure applied to the Log *K(h)* values from years 2015 and 2018 to determine if there is any significant difference between the two years under investigation and the result came out positive as the 2 years significantly differ from each other.

Table 4. ANOVA result showing statistically significant difference identified for multiple comparison procedure by year.

YEAR	*Count*	*LS Mean*	*LS Sigma*	*Homogeneous Groups*
2015	22	-5,2758	0,115113	X
2018	24	-4,67942	0,10517	X
Contrast	*Sig.*	*Difference*	*+/- Limits*	
2015 – 2018	*	-0,596373	0,316225	

* denotes a statistically significant difference

6 DISCUSSION

6.1 EFFECTS OF SOIL TILLAGE TREATMENT ON SOIL PHYSICAL AND HYDRAULIC PROPERTIES

Soil dry bulk density has been considered as a measure of soil quality due to its effect on other soil properties like hydraulic conductivity, porosity and soil water content. Soil dry bulk density is expressed as the ratio of dry weight of soil to total volume of soil. As the ratio of solid in the soil increases, bulk density increases and decreases with a decrease in the ratio of solids. A mutual relationship exists between dry bulk density and soil porosity; as the former increases, the latter decreases and vice versa. From the analysis of the results obtained in the laboratory, the following average dry bulk density values were determined: 1.27 g/cm^3 for RT, 1.21 g/cm^3 for NT and 1.13g/cm^3 for CT. The trend observed for the experimental site were in this order RT > NT > CT showing relatively similar values for RT and NT treatments and considerably lower value for CT plot. The results were not subjected to any statistical analysis due to the limited number of replicates, but the results were in agreement with the research conducted by Mühlbachová et al. (2015) on the same experimental plot at Prague-Ruzyně where RT and NT recorded high values for dry bulk density and CT was characterised by lower values which varied within the three layers measured. Abagandura et al. (2017) observed similar results in CT at the surface layer (0-20 cm) and higher values for RT and ZT which were associated with lack or minimum disturbance at the soil surface.

Various research papers have documented the effect of soil tillage on soil dry bulk density. Špongrová (2010) recorded higher values for NT while CT and RT had similar values which was stated to be as a result of sampling depths (top 10 cm) at which samples were collected. Strudley et al. (2008) concluded that undisturbed and not compacted samples were difficult to collect at depth as they create uncertainty between reported values. Jabro et al. (2016) reported no significant differences between the three tillage systems that were observed during a 4-year experimental phase. However, their result showed that the mean averaged bulk density values over all 4 years and layers for deep tillage (DT) was numerically smaller than shallow tillage (ST) and zero tillage (ZT). Tebrugge and During (1999) documented the changes in dry bulk density over time as a decrease was recorded after CT operations during cold period especially in October and an increase in the month of May. Whereas NT had high bulk density values during those cold periods and low values in May and this was believed to be as a result of the self- mulching characteristics of Eutric Fluvisol being investigated.

Soil porosity describes the portion of the soil that is not occupied by solid and the understanding of pore arrangements and structure is important in the identification of tillage effects on soil physical and hydraulic properties. The result of the experiment showed that CT had the highest value for soil porosity, followed by NT while RT recorded the lowest. The soil porosity for the experimental site were observed in this order CT > NT > RT. The averaged high value recorded for CT could be as a result of disturbance by machinery on the soil surface layer which caused loosening of the soil. Abagandura et al. (2017) also noted an increase in porosity for CT at the surface layer (0-20cm) while at the subsurface depths (20-40 cm and 40-60 cm) were recorded the highest values and this was thought to be as a result of the weight of the machinery which caused an increase in the bulk density of deeper depths. Soils generally have higher porosity under CT than NT within the plough layer and this is related to the findings of Balan et al. (2019) where the values for total porosity was found to decrease with depths in CT and NT. RT was reported to have the lowest value at a depth of 10-20 cm and NT was slightly higher at 0-10 cm depth. In another study, Osunbitan et al. (2005) investigated the effect of Manual tillage (MT), Plough-plough (PP), Plough-harrow (PH) and No-tillage (NT) on some soil hydraulic properties. The total porosity of the surface soil observed during the study increased with the intensity of soil manipulation by tillage, PH and PH had the same porosity values while NT had a smaller value.

Volumetric water content is a numerical measure of soil moisture available in the soil and can be simply described as the ratio of water volume to soil volume. Little differences were found in the averaged values of volumetric water contents obtained on each of the soil treatments; as CT had an averaged value of 0.51 cm^3/cm^3, NT was 0.49 cm^3/cm^3 and RT had 0.48 $cm^3/cm^{3.}$ The observed trend in this experiment showed that an increased porosity for CT equals a high volumetric water content and this had been linked to the loosening of the surface soil which then enabled more penetration of water. The low volumetric water content recorded under RT could be a result of high bulk density which may have caused soil compaction and consequently the low value in water content. However, Jabro et al. (2016) concluded that the averaged moisture content values obtained in their study showed no significant differences among the 3 tillage treatments (ZT, ST and DT) even though small and inconsistent moisture content variations were recorded over a 4-year period at 4 different depths. The inconsistent cases of variation in moisture content among the tillage treatment in some of the soil layers were said to relate to soil variability among plots across field.

6.2 THE EFFECT OF TILLAGE ON UNSATURATED HYDRAULIC CONDUCTIVITY *K(H)*

The unsaturated hydraulic conductivity measures the ability of soil to retain water when the pore spaces are not saturated. The measurement was done with the aid of a Mini Disk infiltrometer on each of the soil treatment. The pressure head was adjusted from -5, -3 to -1 cm and 3 replications have been carried out on each of the soil treatment plot. The averaged values for each of the pressure head on the three treatment plots were presented in Figure 13. NT had the highest values across the three pressure heads but *K(h)* increased with the pressure head as the highest value was noted at -1 cm while CT and RT had not so much differences in their *K(h)* values. This is in line with the study conducted by Kargas and Londra (2015) in which they concluded that hydraulic conductivity was lower in tilled soil than in NT soil at relatively high water contents near saturation. The greater *K(h)* values at -1cm pressure head on NT could be a result of the presence of bigger pores created by soil animals.

Naturally and consistently, the lowest values were observed at pressure head -5cm for all the three tillage treatments. The trend observed was in the order NT > RT > CT and maintained at all pressure heads. The high *K(h)* value for NT could be due to the presence of roots, crop residue and small animals which may have created holes and cracks in the soil. The results of one year long 4-phased experiment conducted by Špongrová (2010) showed that large values were documented for CT and RT at the 2nd phase as the measurements were taken 2 weeks after tillage but this was temporal as the values had decreased at the 3rd phase and decreased further at the 4th phase. However, no such increase was recorded for NT at the 2nd phase. This was attributed to the disturbance of soil on CT and RT which caused the loosening of the surface soil but as the soil settled and formed clods, the subsequent *K(h)* values were decreasing.

Despite the variations found in the *K(h)* values within the soil treatments, statistical analysis showed that no significant difference existed between the Log *K(h)* values of the three soil treatments for the selected significance level (α = 0.05). However, the result of multiple comparison procedure identified a significant difference between the Log *K(h)* obtained at each of the pressure heads on the different treatment plots where the most variation was found between the pair of pressure heads -1 cm and -5 cm.

6.3 THE EFFECT OF TILLAGE ON SATURATED HYDRAULIC CONDUCTIVITY *KS*

Saturated hydraulic conductivity *Ks* measures the ease with which the pores of saturated soil transmit water. Both field and laboratory measurements were conducted to determine the saturated hydraulic conductivity. The field measurement involved the use of Pressure infiltrometer (Matula and Kozáková, 1997) to obtain five replicates on each of the soil treatment plot. In the laboratory, automated KSAT View Device which implemented the falling head method was used to determine the *Ks* of collected core samples. The field measurements were evaluated in an Excel spread sheet and averaged *Ks* value of 1.09E-04 m/s for CT was the highest, followed by RT with 7.18E-05 m/s and NT with the lowest value of 3.72E-05 m/s. Even though the averaged values obtained with the KSAT View Device for CT and RT seemed close, the trend (CT > RT >NT) was maintained as with that of Pressure infiltrometer. The averaged values of 3.00E-04 m/s, 2.27E-04 m/s and 8.41E-05 m/s were obtained for CT, RT and NT respectively. The high value obtained for CT and NT could have been as a result of macropores formed over the years by various tillage operations. This was in line with the Špongrová et al. (2010) where the effect of tillage operations was found to have increased infiltration rates on CT and RT plot after 15 years of management practices.

The variance components involved in the experiment were analysed to determine the factor that contributed the most to the variations amongst the Log K(h) and the result reavealed infiltration type as the factor with the most contributions. The trend amongst the infiltration type used was observed as KSAT > Pressure infiltrometer > Minidisk. Both KSAT View Device and Pressure infiltrometer (Matula and Kozáková 1997) measured the saturated hydraulic conductivity while Mini Disk measured the unsaturated hydraulic conductivity and the *Ks* was estimated by extrapolation. In Figure 20, it was clear that KSAT and Pressure infiltrometer shared little to no difference between them but when compared with Mini Disk, they presented a large gap. The variations could be as a result of agreement that seemed to exist between the results of KSAT and Pressure infiltrometer as they both showed the order as CT > RT > NT and an indication of macropores which Mini Disk infiltrometer was unable to cover in its whole extent.

6.4 COMPARISON BETWEEN THE DATA COLLECTED IN 2015 AND 2018

In order to characterise a possible time effect on the hydraulic properties of soil on the CT, RT and NT plots, the collected data from 2015 were subjected to the identical data analysis as data from 2018. Although the measurements were taken at approximately the same time of a year, very different weather and soil moisture conditions have been recorded for the years 2015 and 2018. Based on the provided data records, measurements in 2015 were carried out during a wet and cool weather conditions (a chart showing the weather conditions during experiment can be found in Figure A1 in Appendices). The result of the unsaturated hydraulic conductivity measured with Mini Disk showed that at pressure head -1cm, CT (2.78E-06 m/s) recorded higher *K(h)* values than RT(1.02E-06 m/s) and NT (8.20E-08 m/s). The role of initial soil moisture content can play an important role especially when the Mini Disk infiltrometer is used. A significant decrease in *K(h)* values measured by the Mini Disk infiltrometer with increasing value of the initial soil moisture content has been reported by Lufinková et al. (2015). The same trend has been observed in this study. Different trends for years 2015 and 2018 were recorded; CT > RT >NT and NT > RT > CT respectively. This correlated with the review of Strudley et.al (2008) where it was noted that changes in soil hydraulic conductivity occurs with time and space, especially unsaturated hydraulic conductivity that could change dramatically in time with moisture state.

For saturated hydraulic conductivity measurements which were determined by Pressure infiltrometer (Matula and Kozáková, 1997), the values of Log *K(h)* was noted to be relatively high for NT and RT as compared to CT in year 2015. Between years 2015 and 2018, the trend for Log *K(h)* values were NT > RT > CT and CT > RT > NT respectively. Similarly, Schwen et.al (2011) analysed the time-variable effects of seasons on *Ks* and reported a decrease in the values of CT and RT after tillage. This was associated with precipitation induced pore settling and sealing effect on the soil and a gradual increase was also documented in spring and summer probably due to root development or biological activities. The two experiments were conducted on the same plot and one of the reasons that could have been responsible for the change is the alternation of the tillage systems on the experimental site as this could have influenced the hydro-physical properties of the soil. Also, the crops grown within these periods could have been a source of the change as a result of root development.

ANOVA identified a significant difference in the Log *K(h)* values among the infiltration type used in years 2015 and 2018. The Pressure infiltrometer had a higher value and was significantly different to the Mini Disk infiltrometer. The probable reason for this could be not only the different soil moisture conditions a presence of visible cracks on soil in 2018, but also the size of data set as the number of replicates collected varied between the infiltration types used. In 2015, 2 replicates were obtained at pressure heads -5 cm and -1 cm for each of the soil treatment as the exercise was said to be hindered by the wet soil. Whereas in 2018, 3 replicates were measured at pressure heads -5, -3 and -1 cm for each of the soil treatment.

7 CONCLUSION

Saturated and unsaturated hydraulic conductivity together with the parameters of the retention curve are the most important hydraulic properties of each soil. Practically all environmental models dealing with the possible water movement involve hydraulic conductivity as input data. The field measurement of these characteristics is rather time-consuming and thus costly. Moreover, these characteristics are changing in space and time and no reference method for their determination exists. That is why the *K(h)* and *Ks* data can be compared to each other only relatively. The *K(h)* and *Ks* values for silty clay loam soil under CT, RT and NT treatment have been evaluated in this study. Time effect has been characterised on the basis of K*(h)* and *Ks* data comparison between the years 2015 and 2018. Clear differences between the soil treatments have been observed. However, the differences were not statistically significant and were not consistent for the years being compared. The reason for that can be found in high *K(h)* and *Ks* variations, completely different initial soil water conditions for the infiltration experiments and different plants being grown on the experimental plots (winter wheat in 2018, and pea in 2015). These are probably also the reasons why the *K(h)* and *Ks* values obtained in 2018 were significantly higher than those determined in 2015. As a result, the null hypothesis characterising no significant effect of soil treatment on *K(h)* and *Ks* has been accepted for this particular study area and time of measurement. The year 2018 was extremely dry and the soil conditions in the field were relatively difficult due to presence of big cracks and animal holes in the experimental area causing high variations of *K(h)* and *Ks* data within the individual treatments.

When the NT system enables growing of crops in comparable soil and soil-water conditions with the comparable yield as RT and CT it would mean a significant energy and money saving for the farmer. But this is not the case, as the results are not supporting it completely. Crop yield study carried out for this particular study area conducted by Mühlbachová et al (2015) is showing a decrease in crop yield on NT plot; suggesting that at least some treatment of the topsoil is beneficial at this site. Some recommendations for further work extending research results of this study are listed below:

- Due to the tedious and time-consuming nature of the field measurements of hydraulic conductivity, the use of models should be considered in the prediction and determination of soil hydraulic conductivity.

- Also, a detailed study characterising the root effect of crops grown on soil hydraulic conductivity should be considered. Especially for this experimental site which had been in use for several years for the cultivation of various crops.

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9 LIST OF FIGURES

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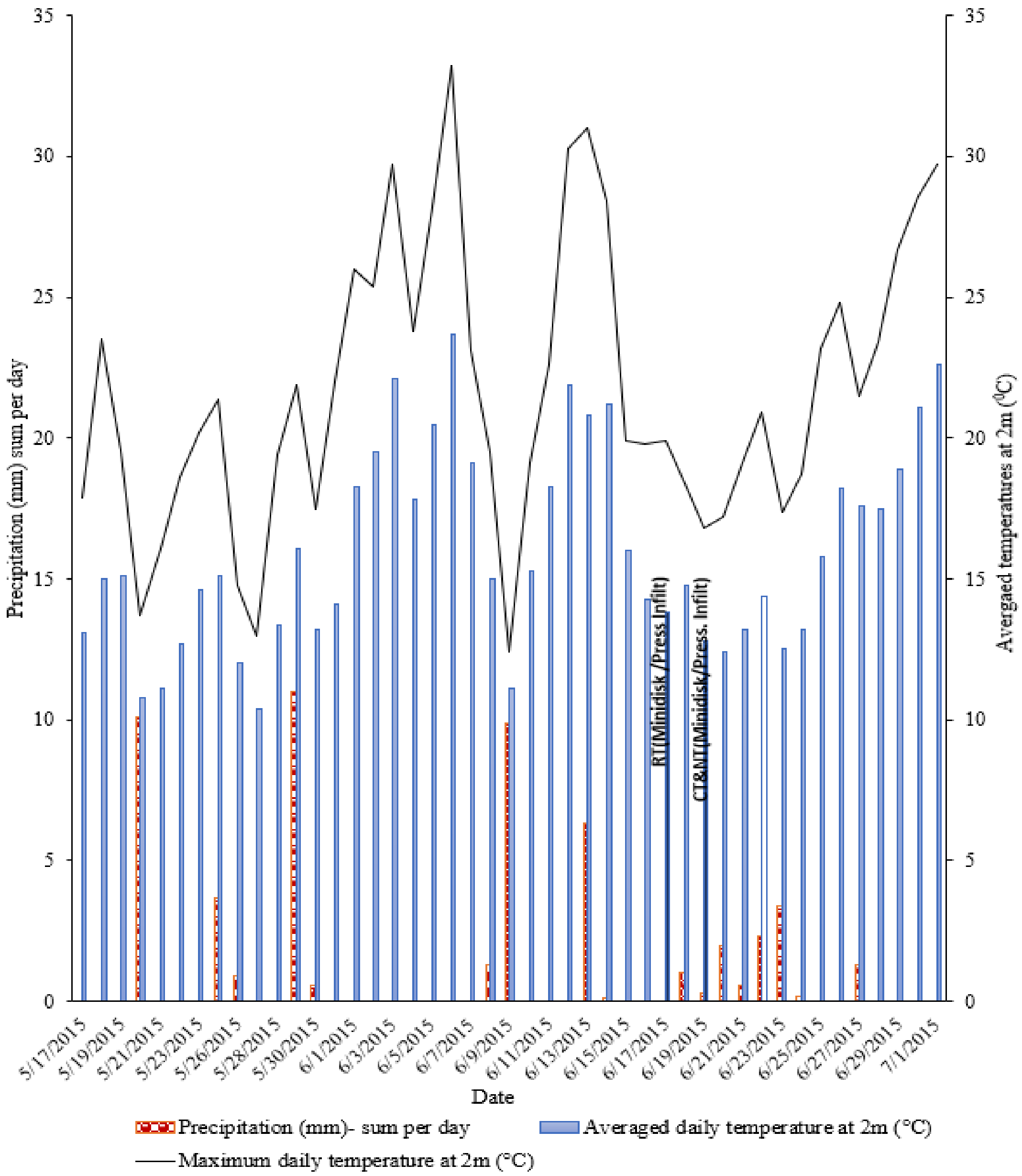
11 APPENDICES

Appendix 1

Weather conditions during the field experiment in year 2015 (Data source: Agrometeorological station, Crop Research Institute Prague)



Appendix 2

Overview of all *K(h)* and *Ks* data determined in the field and laboratory by different infiltrometers in 2015 and 2018

YEAR	INFILTRATION TYPE	REPLICATE	TREATMENT	TENSION	Kh (m/s)	Log Kh
2015	Minidisk	1	RT	5	4.042E-07	-6.3934
2015	Minidisk	2	RT	5	4.042E-07	-6.3934
2015	Minidisk	3	RT	5	4.042E-08	-7.3934
2015	Minidisk	1	RT	1	8.648E-07	-6.06307
2015	Minidisk	2	RT	1	2.100E-06	-5.67772
2015	Minidisk	3	RT	1	9.884E-08	-7.00508
2015	Minidisk	1	NT	5	3.133E-06	-5.5041
2015	Minidisk	2	NT	5	6.177E-07	-6.2092
2015	Minidisk	1	NT	1	4.042E-08	-7.3934
2015	Minidisk	2	NT	1	1.235E-07	-6.90817
2015	Minidisk	1	CT	5	2.021E-07	-6.69443
2015	Minidisk	2	CT	5	9.095E-07	-6.04122
2015	Minidisk	1	CT	1	1.235E-06	-5.90817
2015	Minidisk	2	CT	1	4.324E-06	-5.3641
2018	Minidisk	1	RT	5	1.213E-06	-5.91628
2018	Minidisk	2	RT	5	8.084E-07	-6.09237
2018	Minidisk	3	RT	5	1.011E-06	-5.99546
2018	Minidisk	1	RT	3	3.799E-06	-5.42033
2018	Minidisk	2	RT	3	3.129E-06	-5.50465
2018	Minidisk	3	RT	3	2.682E-06	-5.5716
2018	Minidisk	1	RT	1	6.425E-06	-5.19216
2018	Minidisk	2	RT	1	8.031E-06	-5.09525
2018	Minidisk	3	RT	1	5.683E-06	-5.24541
2018	Minidisk	1	NT	5	2.021E-07	-6.69443
2018	Minidisk	2	NT	5	5.053E-07	-6.29649
2018	Minidisk	3	NT	5	1.011E-05	-4.99546
2018	Minidisk	1	NT	3	8.939E-07	-6.04872
2018	Minidisk	2	NT	3	7.821E-07	-6.10671
2018	Minidisk	3	NT	3	5.587E-05	-4.25284
2018	Minidisk	1	NT	1	2.224E-06	-5.65289
2018	Minidisk	2	NT	1	2.347E-06	-5.62941
2018	Minidisk	3	NT	1	1.359E-04	-3.86677
2018	Minidisk	1	CT	5	7.074E-07	-6.15036
2018	Minidisk	2	CT	5	7.074E-07	-6.15036
2018	Minidisk	3	CT	5	1.213E-06	-5.91628
2018	Minidisk	1	CT	3	1.117E-06	-5.95181
2018	Minidisk	2	CT	3	2.011E-06	-5.69654
2018	Minidisk	3	CT	3	2.235E-06	-5.65078
2018	Minidisk	1	CT	1	3.212E-06	-5.49319
2018	Minidisk	2	CT	1	2.842E-06	-5.54644
2018	Minidisk	3	CT	1	3.706E-06	-5.43104

YEAR	INFILTRATION TYPE	REPLICATE	TREATMENT	Kh (m/s)	Log Kh
2015	Pressure infiltrometer	1	RT	1.814E-06	-5.741298778
2015	Pressure infiltrometer	2	RT	1.101E-04	-3.958035455
2015	Pressure infiltrometer	3	RT	1.690E-06	-5.772207685
2015	Pressure infiltrometer	4	RT	6.148E-05	-4.211276003
2015	Pressure infiltrometer	5	RT	6.864E-05	-4.163424171
2015	Pressure infiltrometer	1	NT	6.924E-05	-4.159645781
2015	Pressure infiltrometer	2	NT	1.481E-05	-4.829394669
2015	Pressure infiltrometer	3	NT	5.068E-06	-5.295166885
2015	Pressure infiltrometer	4	NT	7.463E-06	-5.127115181
2015	Pressure infiltrometer	5	NT	3.700E-04	-3.43174096
2015	Pressure infiltrometer	1	CT	7.700E-06	-5.113506855
2015	Pressure infiltrometer	2	CT	2.091E-05	-4.679702706
2015	Pressure infiltrometer	3	CT	9.786E-06	-5.009392715
2015	Pressure infiltrometer	4	CT	5.087E-05	-4.293561358
2015	Pressure infiltrometer	5	CT	1.520E-05	-4.81804563
2018	Pressure infiltrometer	1	RT	4.899E-05	-4.309859218
2018	Pressure infiltrometer	2	RT	6.076E-05	-4.216380093
2018	Pressure infiltrometer	3	RT	6.838E-05	-4.165057669
2018	Pressure infiltrometer	4	RT	8.566E-05	-4.067202791
2018	Pressure infiltrometer	5	RT	9.538E-05	-4.020529163
2018	Pressure infiltrometer	1	NT	4.565E-05	-4.340529887
2018	Pressure infiltrometer	2	NT	5.773E-05	-4.238577262
2018	Pressure infiltrometer	3	NT	2.970E-05	-4.52721422
2018	Pressure infiltrometer	4	NT	1.264E-05	-4.898166508
2018	Pressure infiltrometer	5	NT	4.036E-05	-4.394002957
2018	Pressure infiltrometer	1	CT	2.371E-04	-3.625137683
2018	Pressure infiltrometer	2	CT	7.063E-05	-4.151016285
2018	Pressure infiltrometer	3	CT	7.069E-05	-4.150628062
2018	Pressure infiltrometer	4	CT	1.113E-04	-3.953560173
2018	Pressure infiltrometer	5	CT	5.314E-05	-4.274616671

Year	Infiltration type	REPLICATE	Treatment	Ksat values	Dry bulk density (g/cm3)	Log Ksat
2018	K-Sat	Sample 1	RT	1.212E-05	1.42	-4.9165
2018	K-Sat	Sample 2	RT	4.060E-04	1.19	-3.39147
2018	K-Sat	Sample 3	RT	2.637E-04	1.22	-3.57894
2018	K-Sat	Sample 4	NT	1.458E-04	1.19	-3.83624
2018	K-Sat	Sample 5	NT	5.604E-05	1.23	-4.25148
2018	K-Sat	Sample 6	NT	5.054E-05	1.20	-4.29636
2018	K-Sat	Sample 7	CT	2.607E-04	1.14	-3.58391
2018	K-Sat	Sample 8	CT	3.386E-04	1.12	-3.47037