CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

Faculty of Agrobiology, Food and Natural Resources

Department of Water Resources

Czech University of Life Sciences Prague
Faculty of Agrobiology,
Food and Natural Resources

Conversion of Classical Systematic Drainage into Regulation Drainage

DIPLOMA THESIS

Author: Selma Hasić, BSc.

Supervisor: Prof. Dr. Svatopluk Matula

Prague 2020

Declaration

I hereby declare that I have completed this thesis titled Conversion of Classical Systematic Drainage into Regulation Drainage independently, all texts in this thesis are original, and all the sources have been quoted and acknowledged by means of complete references and according to Citation rules of the FTA.

In Prague, July 24, 2020

....

Selma Hasić

Acknowledgements

This thesis is dedicated to my brother Jasmin for supporting me in my lifelong intellectual pursuits.

I would like to thank to my supervisor Dr. Svatopluk Matula for his support throughout the writing process.

I would like also to thank to my dear colleagues Kara Recep Serdar and Almaz Cansu for their encouragement and help.

I'm thankful to the Czech Government for supporting my Master studies and for granting me the opportunity to pursue my academic interests and goals.

Finally, special thanks go to my family and my close friends, especially to Ajla, Amra and Minela for their encouragement and support.

Summary

Nowadays, many countries are investing resources and efforts into developing new methods and models to achieve sustainable water management. There are many ways to realize this goal, and controlled drainage is considered to be one of the successful ways to conserve and protect water resources.

Different types of control structures for application of controlled drainage were installed and tested in the Czech Republic in 1980's, at various locations. Changes in political system in 1990's also led to changes in management of the drainage systems, which in some cases resulted in improper maintenance.

This thesis aims to contribute to an ongoing research in the field, by focusing on whether improper and insufficiently accurate use and maintenance of the controlled drainage systems, over a significant amount of time, can affect its overall functioning and feasibility. This is done by investigating the current hydropedological situation of a controlled drainage at Kolesa Vapno site (Pardubice region), and by mapping the measurable and verifiable changes that occurred in the past 30 years. The potential changes were observed through analysis of several parameters, such as water content (gravimetric and volumetric), particle density, saturated hydraulic conductivity (Auger hole method and KSAT) and particle size distribution (Hydrometer method).

Keywords: Controlled drainage, sub-irrigation, hydrpedological survey, particle size distribution, hydraulic conductivity, Czech Republic.

Table of Contents

List of Figures and Tables

List of Abbreviations

CAP- Common Agriculture Policy

CDS - controlled drainage system

EC – European Commission

EU – European Union

FAO- Food and Agriculture Organization

GAEC- Good agricultural and environmental conditions

PSD- Particle size distribution

PVC - Polyvinyl chloride

SMR- Statutory Management Requirements

USDA- United States Department of Agriculture

UN – United Nations

UNDP – United Nations Development Programme

1. Introduction

Between 1980 and 1982, a controlled drainage structure was installed and tested in one of the rural locations near small villages Kolesa and Vapno located in the vicinity of the City of Pardubice (henceforth Kolesa-Vapno), with aims of testing the effects of this type drainage on production and soil conservation.

Later, the property of the land on which the regulation (in text: controlled drainage) system operated was transferred to private owners, who had completely taken over its management (Tlapakova, 2017). However, the new titleholders were not instructed properly about the key properties of the controlled drainage system in their possession, so the entire management process was incompletely and insufficiently operated or not used at all. From early 1990's till today, the entire system's operation was not optimally serviceable and was underutilized, which created a number of side effects in outputs and its overall functionality. Additional unfitting method of privatization of drainage structures, combined with poor handover of structures without proper information and technical documents, have altogether potentially led to some negative consequences.

This thesis focuses on field-testing of the main parameters related to the viability and sustainability of the controlled drainage system built in Kolesa-Vapno, in order to test the feasibility of rehabilitation of controlled structures. The field-testing is intended to reveal the current situation of hydropedological parameters and detect the changes that had potentially occurred due to the lack of proper maintenance. The research will be focused on new initial survey which includes field observation and testes of water content, particle density, particle size distribution, hydraulic conductivity and propose several factors and venues for further research in order to measure and evaluate the viability of controlled drainage systems which have not been properly used for water management for a certain period of time.

2. Scientific Hypothesis and Objectives of Work

Almost 30 years of laxity in maintaining the said controlled drainage system called for exploration of its viability and sustainability, in order to determine whether management mishaps might have deteriorated its overall features and use. This research was thus guided by the following research questions:

- In what way did the improper and insufficiently accurate use and maintenance of the controlled drainage system in Kolesa-Vapno in the past 30 years, affect its overall functioning and feasibility?

- In which particular tested parameters of system's functioning are the changes most noticeable?

In order to facilitate the outlined research questions, the following hypotheses will be tested:

H_0 > there are no significant changes in the current system's functionality and overall serviceability as a result of improper management in the past 30 years, since the management of the system was transferred to private owners and not used as initially designed. The tested parameters show no significant changes.

H_1 > there are significant changes in the current system's functionality and overall serviceability due to the improper maintenance, and they are most noticeable in the following measured parameters: water content (gravimetric and volumetric), particle density, saturated hydraulic conductivity (Auger hole method and KSAT) and particle size distribution (hydrometer method) (cf. Libohova et al, 2018; Hill et al, 2018).

To answer the proposed research questions and test the outlined hypotheses, this thesis will proceed with the analysis and contextualization of pertinent literature and comparable empirical findings in other controlled drainage systems, and a desk review of the relevant available documentation on this particular system's operation and maintenance. It will be completed with an applicable analysis of the soil samples collected at the research site, interpretation of the results, and suggestions for further research.

3. Literature Overview

The current world population is projected to increase by 1 billion by 2025, and reach 9.6 billion by 2050 (UN, 2019). The global expansion of population will inevitably lead to an increase of agricultural production that would need to sustain the demands. Many arable land areas around the world have already reached their limits for further expansion in production. Our knowledge of the production potential of the world's land resources is rather crude: roughly 20 percent of the land surface was considered too cold, 25 percent too dry, 20 percent too steep or too shallow, 5 percent too wet and 10 percent of too low fertility for agricultural production; 20 percent of the world's lands were estimated to be arable, about half of this being currently in use (FAO, n.d.) The overall agreement among the scientists is that the current arable land production capacities do not match the degree of population growth, and this is why people have to monitor and control the patterns of future sustainability in order to be able to provide enough food for growing human needs. This would also depend on sustainable development that includes different parameters, inter alia, new technologies, environmental protection, financial assessment, and human resources. On a global level, these parameters are also connected with climate change, inflation, and international trade (cf. Owens and Cowell, 2011).

The rational use of available land resources is closely connected with the use of the clean water to sustain the food production. In order to achieve sustainable water use, i.e. increase quality of water and decrease use of water, some gaps need to be fulfill such as: improving operation and maintenance of irrigation and drainage systems what implies on rehabilitation and modernization of systems which will include water intakes, protection of sediments, reduction of fertilizers and pollutants of agriculture (cf. Schyns et al., 2019). These processes also include education of farmers, adoption and promotion of agricultural researches and institutional reforms related to ownerships of drainage systems (De Wrachien, 2001).

In order to efficiently deal with these issues, various countries have set regulations in order to improve the current situation and achieve high levels of sustainability in water use. The European Union, for example, set regulations for sustainable water management in agriculture through Common Agricultural Policy (CAP).[1] It relies on the complementary effects of various instruments: cross-compliance, the green direct payment, and rural development support measures (Vanham et al, 2015). The first cross compliance refers to direct measures, such as SMR 1 on Nitrates Directive, GAEC 1, 2 and 3 on buffer strips to protect surface water, groundwater pollution and irrigation. Others are indirect, like GAEC5 on limiting erosion, GAEC 7 on landscape features providing ecological services, or SMR 10 on pesticides. The second cross compliance is devoted to rural development, and it includes sustainable management of natural resources trough improvement of water management, i.e. reduction of fertilizers and pesticides, and the increase of efficiency in water use by agriculture (European Commission, 2017).

One of the readily available and feasible options to achieve a sustainable water (re)use, especially in agricultural production, is building new and rehabilitation of the existing *drainage systems*. Until the 20th century, individual farmers performed the installation of drainage systems. Their design was established based on experience of local communities (Valipour et al, 2020).[2] Nowadays, drainage systems became one of the sources of pollutants, as they produce higher level of harmful nutrients from fertilizers, pesticides, and sediments (Kroger et al, 2008).

Many researches and practitioners have tried to evaluate and compare the environmental impacts of ‘older-traditional’ and ‘new-innovative’ agricultural drainage systems. Many countries, such as the United States and some other in the EU, have developed models to achieve high levels of sustainability water use in agriculture called controlled drainage systems. Unlike in the conventional drainage systems, where pipes drain the water freely into the drainage ditch, and the water is drawn from the field when groundwater level rises above the drain level, the ‘controlled drainage’ system can

---

[1] The Green Direct Payment is indebted to improve the environmental act of the CAP (with water included). According to Rural Development Programs (RDPs), prediction for 2014-2020 is improvement of water management on 15% of agricultural and 4.3% of forestry land in the EU (European Commission, 2017).

[2] The first forms of ‘drainage systems’ were linked to oldest civilizations of Mesopotamia and Iran before 4000 BC. Development of strategies and techniques of drainage systems in period BC were also recorded in Eastern Mediterranean, Minoan, Mycenaean, Egypt, China, India, Maya, Inca, Hellens, Romans, and other civilizations from that period. Techniques for drainage systems until second half of 18th century were very limited, when recovery of agriculture took place. Development of agriculture encouraged mechanical production of drainpipes firstly in England and then in the other parts of Europe and the USA (cf. Valipour et al. 2020).

be managed to level up the water use, so it has the possibility not to drain water through the pipe channels when the groundwater is above the drain level (Staarnik, 2014).

There were only a few controlled drainage systems built in the Czech Republic in the last 40 years, some during the ‘communist era’, and some since the country reestablished its full independence and later joined the European Union. There are several locations where controlled drainage systems were built: Starý Kolín, Kolesa-Vápno, Bulhary-Přítluky, Lehota, Živanice and others.

3.1. Use and Types of Conventional Drainage Systems

There are different types of drainage systems. Their design and use depend on geographic and climate-related factors. Throughout the history, engineers attempted to develop the best possible drainage systems, primarily, to be used in agriculture to improve crop production. However, the conditions for successful crop production depend on natural conditions of specific agricultural area, so agricultural drainage has to meet different needs for dry and humid areas. In humid areas, the aim of drainage system is to reduce damage to crops, which can occur due to abundant precipitations and also to control soil water conditions for better aeration, workability and temperature regime. On the other hand, in arid areas, drainage system should prevent the accumulation of abundant amounts of salts and represent proper solution after heavy irrigation or monsoons (Molen et al, 2007). The conventional (also known as traditional, free drainage, uncontrolled) engineering-based techniques are most commonly used to drain excess water from land are: surface and subsurface drainage (i.e. horizontal subsurface drainage and vertical subsurface drainage).

3.1.1. Surface Drainage

The term 'surface drainage' refers to drainage used in situations where main flow of excess water is achieved through overland flow, so it habitually involves open drains and can include construction of broad-based ridges or beds, as grassed waterways, with the water being discharged through the depressions between ridges. Generally, it is the most important drainage technique for the humid and sub-humid zones. Surface drainage is applied on soils with low permeability, soils which have shallow permeable layer, where impermeable layer is between 2.5 and 6 meters, unequal land surface, which consist out of pockets or ridges that slow or stop natural runoff, and as an addition to subsurface drainage (USDA, 2001).

3.1.2. Subsurface Drainage

Subsurface drainage systems are usually installed in order to make a control of the ground level water (Molen et al, 2007). There are many advantages of subsurface drainage, inter alia, aeration to root zone, improvement of soil structure and maintenance of soil temperature, easy movement of farm machines, removal of large amount of salts from the root zone, no occupation of surface land, small capacity and lower maintenance cost. However, some disadvantages can be distinguished as well, such as high costs for installation, need for steeper gradient, construction and repair costs. In Europe, the first drainage subsurface systems were built at the beginning of the Christian period, but this kind of drainage system did not play the big role in next period. High speed installation techniques were provided by appearance of fuel engines in 20th century, which enabled further development of subsurface drainage (Valipour et al, 2020).

Horizontal subsurface drainage can be formed as a singular or composite system. Singular system consists of open trenches or laterals flowing into open outlet drains. Composite drainage systems are the most common and formed as a network of pipes (i.e. collector drains) installed horizontally and discharged into the main outlet system. Even though it is called horizontal subsurface drainage, these drains generally have some slope (Molen et al, 2007). In the past 60 years, there was a rapid increase of the installation methods and drainage materials such as pipes and envelopes (Vapouir et al, 2020). At the beginning, the pipes were made from clay, but in 1960s, this material was replaced with PVC, since it was more resistant, available and could be purchased at lower prices. Envelopes were made from fine, well-graded gravel, pre-wrapped organic materials (peat), natural fibers or woven/non-woven synthetic materials, because they prevent the entrance of the soil particles, but at the same time, they promote the flow of the water (cf. Stuyt et al, 2005).

The water in drains installed at relatively shallow depths with a smaller spacing may contain less salt, thus reducing salt loads of the drainage water. At the same time, the volume of discharged drainage water may be less compared with deeper, wider-spaced drains. This is because much of the flow pattern does not extend as deep into the poorer-quality groundwater. As a result, the relatively better-quality shallow groundwater was skimmed off near the water table and contributed more to the total discharge of subsurface drainage (Valipour, 2014).

Vertical subsurface drainage is drainage system used for removal of groundwater through properly spaced pumped wells. This type of drainage can be useful in the presence of unconfined or semi-confined aquifer. Where drainage is undertaken by pumping of aquifers, typically by tube well or spear point systems, there is a risk of aquifer salinization. This is especially the case where small aquifers surrounded by salt laden aquitards (e.g. clays) are over pumped. This causes the migration of salts from the aquitard into the aquifer. However, when the soil consists of a poorly permeable top layer several meters thick, overlying a rapidly permeable and deep subsoil, wells may be a better option, because the drain spacing required for pipes or ditches would be very narrow, whereas the well spacing can be very wide. This type of drainage can be quite complicated, and data of the geology of place and permeability of soil and subsoil need to be precise (USDA, 2001).

3.2. Conversion of Drainage Systems as Important Parameters of Sustainable Water Management

In the past, almost all irrigation and drainage systems were designed and built to last for more decades, and there was no assumption that climate conditions would change rapidly and dramatically. Nowadays, any proper management and institutional adaption would need to be in place due to fixing flexibility of the different systems that will cope with the climate changes. Thus, more focus was placed on having a proper management, rather than construction of new systems that were important in the past (De Wrachien, 2001).

Installation of conventional drainage systems led to the installation of irrigation system. However, their inadequate installation resulted in problems related with water logging and occurrence of salinity (Ballantine and Tanner, 2013) and to the implementation of systems without further management. Namely, the conventional drainage systems only have ability to remove excess soil water, but in addition to this, controlled drainage system increase water retention and storage for water in the soil profile. This ability of controlled drainage system leads to effectiveness in reduction of drained water and nutrient loss (Skaggs et al, 2012). Setting up a successful design and management of water resources assumes availability of hydro-climatic data (De Wrachien, 2001). If adequate management and operation are to be included, a controlled drainage system would have a great potential to be beneficial both for agriculture and environment. Controlled drainage can be defined as flexible management system (Ballantine and Tanner, 2013). They have several purposes: improving efficiency of water use, maintaining crop production during water stress, reducing nutrient losses, and generally ensuring maximal benefit of farmers due to climate change. Controlled drainage belongs to SCIEN (Sustainable, Controlled, Intelligent, Environmental friendly and Nutrient loss mitigating drainage) technologies. They combine different types of drainage with new technologies in order to achieve the most efficient circulation of nutrients (Foged and Hvid, 2012).

Controlled drainage systems, in terms of its structure in form of water control, are more active and manageable, which is especially important today, as global warming contributes to drying out of many areas. Nowadays, management and rehabilitation of drainage systems are not on acceptable level due to lack of global decisions related to improving drainage systems. Countries such as Israel, Netherlands, Russia, Denmark, Korea, the UK, Sweden, Mexico, Lithuania, Austria, Poland, Australia and Slovenia have sufficient drainage and better results for salinity and waterlogging. On the other hand, Switzerland, Germany, Finland and Italy, even with substantial drainage systems still suffer from waterlogging and/or salinity problems. Meanwhile, in France and Portugal, rehabilitation of drainage systems need to be increased to avoid mentioned problems in the future (Valipour, 2014).

3.3. Reasons for Implementation of Controlled Drainage

Various countries require sustainable management of water resources in order to solve different problems such as uneven distribution of water in the world (dry and flooded regions), water scarcity, climate change, overconsumption of water, salinization and pollution of water.

Water scarcity is among the main problems to be faced by many countries in next 50 years. The UNDP (2006) defined water scarcity “as the point at which the aggregate impact of all users impinges on the supply or quality of water under prevailing institutional arrangements to the extent that the demand by all sectors, including the environment, cannot be satisfied fully.“

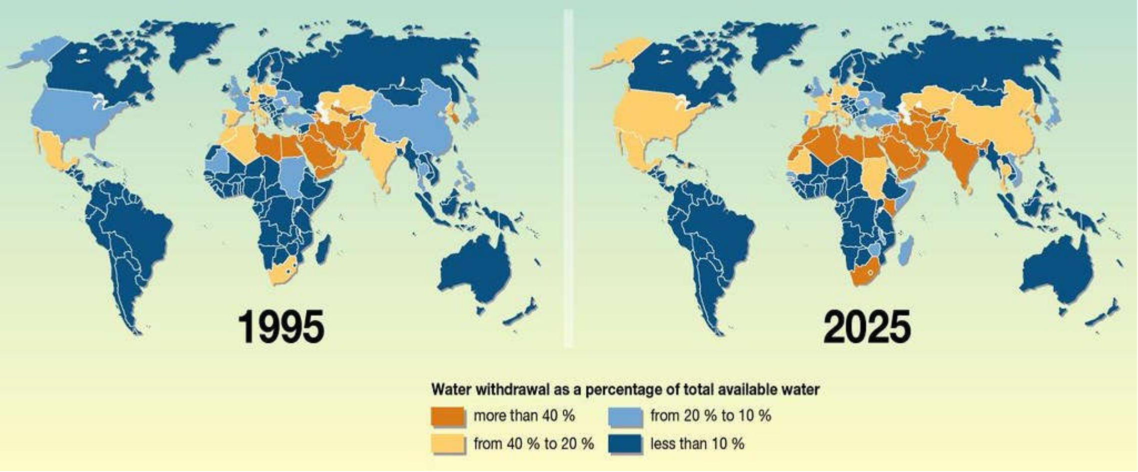


Figure 1: Water scarcity predicted for 2025.

Source: Rekacewicz, 2006

Water scarcity can be caused naturally (i.e. arid regions and climate change) and artificially (i.e. rapid increase of population, overconsumption and non developed strategies). Countries affected by climate change will be exposed to high temperatures and reduced precipitations followed by increased risk of floods, droughts and heat waves. Reduction in surface water and groundwater resources will lead to competition among countries (Sojka et al, 2019). Predictions of areas with water scarcity are based on relative water scarcity index (UNDP, 2006). According to scarcity of water in the world, areas with the greatest potentials for application of controlled drainage are located in regions Major River Basins in Arid and Semi-Arid zones, areas where the mean annual rainfall is less than 500 mm and other areas of predicted future water scarcity identified by the International Water Management Institute (Abbott et al, 2002).

Arid regions also need new developed water management to reduce the negative trends of increased soil salinity in irrigated lands (Ritzema and Stuyt, 2015). Soil salinity can be caused by many anthropogenic actions such as the over-exploitation of natural resources, insufficient management of water resources (not proper irrigation), inadequate methods of land use, or as a result of climate change which can cause unpredictable situations (FAO, 2016). Due to capillary rise or irrigation, saline groundwater has effects on plants and hence agricultural production in terms of crop yield and crop quality. Higher amounts of salts can be found in drains or rivers and wetlands, due to the increase of hydraulic gradients between groundwater and surface water (Jakeman et al, 2016). On the other hand, in areas with monsoonic climate, water distribution is not uniform throughout the year. These areas have problems with dry periods and continuous floods and waterlogging due to monsoon heavy rainfall. Due to monsoon rainfall, soil is not able to infiltrate water and large amount of the water is discharged to the surface. In this period, groundwater table is high for crop root zone and critical for the crop development (Singh, 1996).

Due to increase of population, agricultural activities became more forceful, striving to produce more food to meet the overall demands. Farmers started to use various chemical compounds (such as pesticides) and enormous amounts of nutrients (especially N and P) to improve yield. Primary macronutrients for plants are nitrogen, phosphorus and potassium. Nitrogen has a main role for plant growth, because it is the part of chlorophyll and the amino acids which make proteins. Phosphorus is the most important component of adenosine triphosphate (ATP), in which phosphate groups are linked with pyrophosphate bonds. Nitrogen (N) is inert and plants cannot use forms of nitrogen from the air. Naturally, nitrogen is fixed by specific bacteria. Most of soil phosphorus (P) is virtually inaccessible. More than 90% of total P is present as insoluble and fixed forms. To add more macronutrients to soil, farmers use fertilizers. Over abundance of nitrogen (nitrogen saturation) increases acidity and leaching of other nutrients. Phosphorous often removed with the rain and high amount of phosphorous can cause algal blooms and eutrophication[3]. Through the years, drainage water which contained pollutants and high content of nutrients water caused environmental and

---

[3] Eutrophication is result of excessive richness of nutrients in body of water, usually due to run-off from the land, which causes a dense growth of plant life (usually specific algae) and cause death of organisms in water due to lack O_2 and change in pH. The European Union reported eutrophication on 22% of river and 37% of lake monitoring stations, as well on coastal areas, mainly in Western, Northern and some Eastern European countries, as well as in the Mediterranean (European Commission, 2017).

ecological impacts, such as flooding, eutrophication, forming of hypoxic zones, loss of habitats for animals, contamination of water for drinking (Fausey, 2005). The water quality can also be poor due to high content of pesticides and microbial pathogens which can originate from animal production units or land application of different manure (Pandey et al, 2014).

3.4. Requirements and Application of Controlled Drainage

Controlled drainage is effective if area poses specific requirements such as flat area, which implies constant slope gradient which should not exceed 1% (Busman and Sands, 2002; Ayars et al. 2006), soils with high permeability (>0.5 m d^{-1}) or shallow groundwater table and with impermeable layer 1-3 m below the surface, so it has the ability to retain water on high position (Ballantine and Tanner, 2013).

Another point worth mentioning is that controlled drainage can be applicable systems with different drain spacing. However, narrower drain spacing will reduce the risk of yield loss due to excess wetness during the growing season (Frankenberger et al, 2004). The United States Department of Agriculture (USDA) suggested distance between laterals should be set in interval of 10-27 meters and average depth of drainpipes should be between 0.8 and 1.2 meters.

Application of controlled drainage can be done on surface and subsurface drainage. Controlled drainage as a type of drainage is set by installing a water control structure. There are two types of water control structures:

- open-ditch flashboard riser structure which is used in field ditches (i.e. surface drainage)
- inline control structure attached and used in subsurface drainage

Figure 2: Installation of water control structure

Source: Poole et al, 2018

Control water structures are installed at the downstream outlet (lowest point). This setting usually depends on other factors, such as legal ownership or local topography. Topography of the place also has an influence on size of the area where the water table is controlled because during the system operation it is important that the water table is maintained at a relatively uniform depth. In that case, the topographical map is considered as an essential tool for dividing area into zones of control to achieve management of drainage system. Controlled drainage can be installed on existing drainage system if existing system can be adapted to control water table without waterlogging. As an alternative, specific drain lines can be blocked or control structures can be installed on individual drains or sub-main collector (Ayars et al, 2006).

3.5. Workability of Controlled Drainage

Traditional drainage system drains out the water at the level of the drainage pipes and the water table depth is either maintained or lowered. Setting of this water table does not signify backup for upward flow which should be efficient for better usage of water by crops. (Ayars et al, 2006). Water control structure in controlled drainage has the ability to raise the water table above the drainage pipes, so saturated zone occurs around the drainage pipes in the soil. Water control structure controls water table during a whole year by inserting/removing stop logs. Stop logs are inserted in the structure in order to control water table immediately after harvest. Stop logs enable rising of water table and preventing water availability for crops and development of the roots. In the spring, before planting, stop logs are removed and water is drained. After planting, stop logs are inserted again in order to store water. Stop logs can be removed from soil before harvesting, and cycle can start again. With this ability, controlled drainage has a huge influence on reduction of drainage volumes; as it leads to increase in groundwater recharge, rise in level of water table and increase in amount of soil water in the root zone. Through management of water table levels, plants have higher chances to develop their root system. During high precipitation periods, plants receive a lot of water, so they do not have to develop roots in deeper zones. However, during dry season, they do not have capability to obtain the water from deeper layers of soil. With application of controlled drainage, farmers have opportunity to control amount of water in shallow and deeper layers of soil, so plants can develop their roots (Poole et al, 2018).

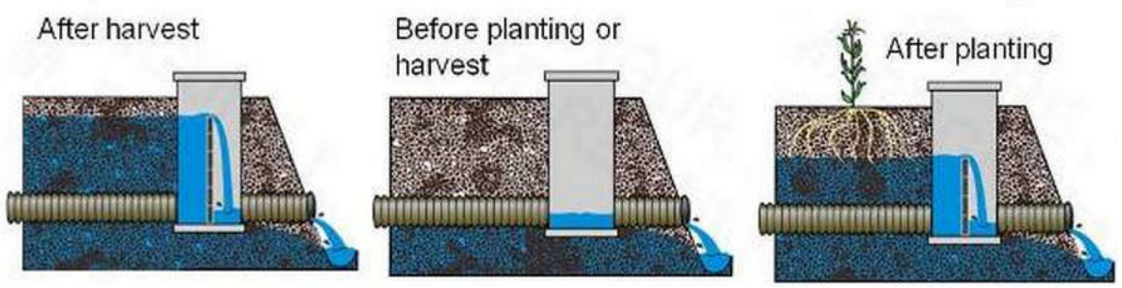


Figure 3: Change of water level in controlled drainage.

Source: Poole et al, 2018

3.6. Controlled Drainage and Sub-irrigation as Dual Purpose Systems

Even though controlled drainage has the ability to reduce water usage, it does not have the ability to sustain water in areas without precipitation at all, so it is not characterized a long term solution for the completely dry areas. However, the application of controlled drainage in dry areas can be expanded if it is used in combination with sub-irrigation as dual purpose system. Controlled drainage and sub-irrigation represent main management of integrated water table in the USA (Vlotman and Jansen, 2003). Management of dual purpose system implies main characteristics of controlled drainage, i.e. raising /lowering of control structure and maintenance of the weir in the control structure on the desired height, together with characteristic of sub-irrigation, such as adding of water to the system in the proper time. Thus, during dry periods, due to sub-irrigation, water can be pumped into the outlet. Response of the crop is slower in sub-irrigation than in conventional systems. Soil should not be too dry before irrigation because hydraulic conductivity will decrease and volume of needed water to raise the water table will increase. Wet soil is capable to move water from the drain to midway between drains in 2-3 days, but dry soil requires 2-3 weeks (Evans et al, 1995).

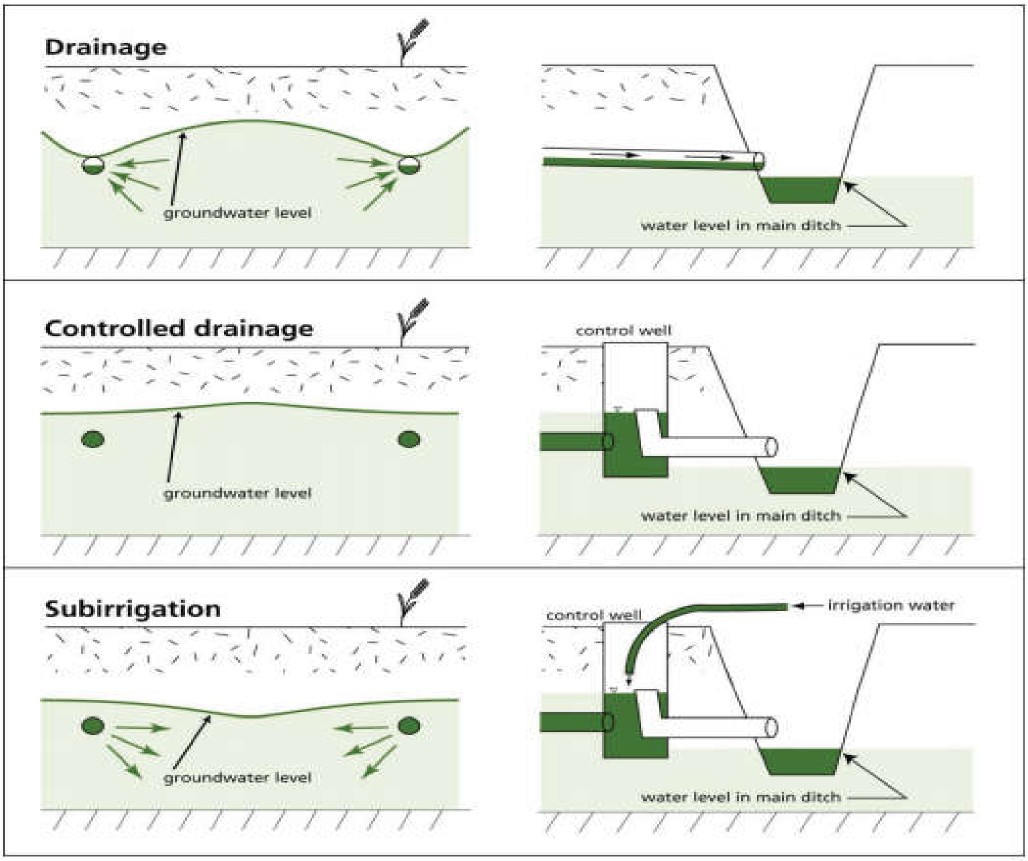


Figure 4: Change of groundwater level due to controlled drainage and sub-irrigation.

Source: Äijö, 2012

Wetland reservoir can be added to dual purpose system as an external water supply for sub-irrigation. Wetland has the ability to capture and store surface runoff. Water from wetland can be used as crop irrigation water. Because of such ability to store the surface runoff, it also serves as a reservoir, which stops the movement of sediments and nutrients, which can be returned (recycled) into the root zone. Using the wetland reservoir, water from precipitation is used more efficiently. In such way, discharge of sediments and other pollutants, which are useful for plants, are reduced in groundwater resources (Tan et al, 2007).

In the past, wetlands were drained and lost the role of sink as storage structure. During the last few decades, some countries have begun the restoration of wetlands to create sinks for nutrients and suspended matter. This restoration had effect on nutrient loss to the Baltic Sea, as observed in Baltic countries as good case practice (Jacks, 2019).

3.7. Application of Controlled Drainage in Other Countries

Controlled drainage (in USA main term for controlled drainage is Drainage Water Management) has the longest tradition in the USA. It was installed during 50's in Florida, to reduce subsidence of drained organic soils, and later in California and North Caroline, to reduce nutrients and prevent eutrophication. Because of its various aforementioned advantages, controlled drainage in some USA states was accepted as the best management practice and promoted by USDA and other federal and state agricultural and environmental agencies. They became popular and gained support, since 1984. More than 4000 water control structures were installed ever since (Skaggs et al, 2012). After the USA, many countries worldwide with different climate features, soil texture, supported by various national and regional institutes, installed and tested controlled drainage to achieve the abovementioned results. Controlled drainage was tested in regions with colder climates such as Ontario and Scandinavian countries to reduce eutrophication in Great Lakes and Baltic Sea, in countries with effects of climate change which cause droughts and floods (for instance Poland, Germany, Netherlands, Italy, Spain) countries with great degree of water scarcity (such as Egypt, Pakistan, Iran and Australia) in order to conserve more water and reduce salinity due to extremely dry periods and areas in subtropical humid monsoon climate zone (south parts of China and India) to stabilize water table in order to prevent expected waterlogging and salinity-affected areas (Wahba et al, 2001; Bonaiti and Borin, 2010; Xiao et al, 2015; Sojka et al, 2019).

3.7.1. Advantages of Controlled Drainage & Best Practices

As outlined above, efficiency of controlled drainage performance and the degree of impact have factors such as climate conditions, soil characteristics, design and management of drainage and field practices (Skaggs et al, 2010). However, application of controlled drainage showed positive results in aforementioned countries with described characteristics below.

The main advantages of controlled drainage such as control of water table, drainage outflow, which lead to reduction of amount of nutrients and pollutants, and potential increase in crop production, were expressed through analysis of research results from different countries sketched in Table 1 below.

Controlled drainage is often called level-driven drainage because of the ability to control and regulate water level or water table. An ability to control water table and drainage outflow is one of the most important features of control drainage for slowing down water scarcity. Water scarcity can lead to other problems with groundwater over-abstractions and resulting water table depletion and salt-water intrusion in coastal aquifers (Vlotman and Jansen, 2003). Surface conventional drainage usually contains higher concentrations of sediments and fertilizer components. Subsurface conventional drainage does not have high amount of sediments, but has high amount of soluble components such as nitrate (Evans et al, 1995). Even though conventional subsurface drainage has positive influence on the agricultural productivity, it also has negative effects, such as increasing the amount of nutrients, released from agricultural areas into close waterway (Jang et al, 2019). The main reason for increasing amount of nitrogen in this case is the fast transport of water, where de-nitrification is prevented to occur. Controlled drainage systems, by setting a higher water level, enhance the process of de-nitrification, which implies conversion of nitrate to form of nitrogen gas (Ayers et al, 2006). The ability of controlled system to hold water in drains and ditches leads to moisturization of soil and availability of nutrients in the soil, so shallow water table creates anaerobic conditions which lead to faster development of de-nitrifying microorganisms (Bonaiti and Borin, 2010).

Table 1: Reduction of water outflow and nutrient loss in observed

Article	**Location and duration**	**Climate**	**Soil texture**	**Depth of drains (m)**	**Space (m)**	**Control of water outflow (%)**	**Reduction of nutrient loss (%)**
Tan et al, 2007	Southwester, Ontario (5years)	Cold, humid	-	0.6	4.6	43	N: 41 P: 18-47
Wesstrom et al, 2002	Sweden, Manstorp 2 years	Cold,semi humid	Loam, sandy loam	1	10	79-94	N: 78-94 P: 58-80
Povilaitis et al, 2018	Lithuania, Lipliūnai	Continental, humid	Sandy loam and loamy sand	0.9-1	10	21-24	N: 42-77 P: 34-72
Helmers et al, 2017	USA, Iowa, Crawfordsville	Continental, humid	-	0.8	12	48-50	N: 40-50
Lavairea et al, 2017	USA,east central Illinois,	Continental, humid	Silty clay loam and silt loam	0.8	15	30-96	N: 30-96
Sojka et al, 2019.	Poland, Poznan	Continental, humid	Sandy loam	0.9-1	14	50-80	-
Bonaiti and Borin,2010	Italy, Padova 6years	Warm, semi-arid	Loam	0.6-1.2	30	77	N:70
Wahba et al, 2001	Egypt, Alexandria	Hot, Semi arid,	Silt loam to clay loam soil	1.2	32	28-68	N: 13-17 P: 30-77
Jouni et al, 2018	Iran, Ardabil Province, (1 year)	Hot, Semi arid	Silty clay loam, after 60 cm silty clay	2	80	33-45	N: 25-51 P: 27-39
Xiao et al, 2015 (1 year)	China, Nanjing	Warm, monsoon	Loamy clay	-	-	-	N:55-66 P: 43
Karegoudar et al, 2019	India, Karnataka,1 year	Warm, semi arid (monsoon)	Clay loam	1.1	50	64	N:50

On average, drainage outflow can be reduced between 15 and 35%, comparing to other measures of uncontrolled systems (Evans et al, 1995; Busman and Sands, 2002; Carstensen et al, 2019) and nitrogen loss varies between 15% and 80% (Evans et al, 1995; Skaggs et al, 2012; Xiao et al, 2015) what depends on design of drainage system, location, soil, and site conditions (Skaggs et al, 2012). All observed sites presented in Table 1. had positive results in reduction of drainage outflow between 11% and 96%. The loss of nitrogen followed the reduction of outflow and in observed sites and varied from 13% to 96%. Level of reduction of N loss can also be different due to different stages of growth (95.6%, 78.7%, 59.6%, and 87.4%) (cf. Lu et al, 2016). A more efficient option for reducing nitrogen loss is controlled drainage combined with Woodchip de-nitrification and it is successful even in colder areas (Husk et al, 2017). Denitrifying bioreactors have to be installed at the end of the drainpipes (Jang et al, 2019). Installing bioreactors, annual nitrate-N loads can be lowered more than 50% (Jaynes et al, 2008).

Studies related to loss of phosphorous levels vary, but evidence that controlled drainage systems can reduce losses of phosphorous exists. The average reduction of concentration of total phosphorus (TP) can be more than 40% (Xiao et al, 2015; Cui et al, 2016). Concentration of P was marked in 6 observed sites and in all cases P was reduced (18-80%). However, some studies reported that practices of controlled drainage increased mobilization of P from within the soil profile (Valero et al, 2007) and increased surface runoff which can lead to soil erosion and water pollution with phosphorus (Skaggs et al, 2010; Sojka et al, 2019).

Some studies also reported reduction of agricultural substances such pesticides, herbicides, which can have hazardous effects water quality. Losses of herbicides usually depend on precipitation after applications of herbicides and intensity of precipitation. Controlled drainage system can reduce losses by holding surface runoff in the soil profile. In this situation, herbicides will adsorb to soil and be degraded by microorganisms or chemical reactions (Ballantine and Tanner, 2013). Controlled drainage also has the influence on movement of pathogens from pipe drains, where system reduces fecal pathogenic bacteria (*E. coli* and *Enterococci*) (Jamieson et al, 2002).

Controlled drainage, by maintaining water table at the shallow depth with irrigation, induce capillary rise into the root zone. In this situation, plants meet part of their evapotranspiration needs directly from soil water instead of irrigation water. Without use of irrigation, the water table gradually drops in areas with no seepage inflow from outside, while a more or less constant water table can be maintained in areas with high seepage inflow. Observed site in India showed reduction of salts in root zone and reduction of salts in Egypt was up to 80% (Wahba et al, 2001; Karegoudar et al, 2019).

As mentioned before, controlled drainage has ability to increase yield by achieving control of water table, drainage outflow and nutrients. While there were substantial positive effects of controlled drainage on measured sites in some cases, there were negligible or not statistically significant effects in others, (showed in table 2.).

Table 2: Influence of controlled drainage on crop yield on observed sites.

Article	Location	Planted crops	Crop yield (%)
Tan et al, 2007 (with sub-irrigation)	Southwestern Ontario	Corn, Soybean	Corn: 7-91 Soybean: 18-49
Wesstrom et al, 2002	Sweden, Manstorp	Cereal and potato	2-18
Povilaitis et al, 2018	Lithuania, Lipliūnai	-	
Helmers et al, 2017	USA, Iowa, Crawfordsville	Corn, Soybean,	No significant increase
Lavairea et al, 2017	USA, Illinois	Corn, Soybean	-
Sojka et al, 2019.	Poland	Wheat	-
Bonaiti and Borin, 2010 (with subirrigation)	Italy, Padova,	Maize, sugar beet, winter wheat, soybean	
Wahba et al, 2001 (with subbirrigation)	Egypt, Alexandria	Maize, wheat	15
Jouni et al, 2018	Iran	Wheat, barley, maize	5-41
Xiao et al, 2015	China, Nanjing	Rice	4 decreased
Karegoudar et al, 2019	India, Karnataka	Rice	0.14-0.25

More precisely, the effect of controlled drainage on yields is very dependent on weather conditions during the growing season. As outlined above, the ability of controlled drainage can potentially increase yield by retaining drainage water in the profile so that it is available to crops during periods without water. However, during long dry growing seasons, there may be little or nil drainage water to conserve so in that case only installation of controlled drainage will not be sufficient and more significant yield responses can be provided if controlled drainage is designed as dual purpose system (Skaggs, 2012). Also, if precipitation occurs at about the right time during a season to satisfy crop evapotranspiration requirements, drainage water conserved by controlled drainage is not needed to satisfy the evapotranspiration demands, and would likely have little effect on crop yield. In that case, the best scenario for increase of yield by controlled drainage is in years when a wet period during the growing season is followed by a moderately long dry period and followed by another wet period, etc. (Skaggs et al, 2010)

Observed sites in table 2. showed that benefits of controlled drainage in increasing relative yield are more significant in the dry and very dry conditions followed by sub-irrigation such in Egypt, Iran and Ontario with increase of crop yield by 15% 41% and 91% than in the normal conditions such as in observed sites in the USA where there was not significant increase of the yield. Sites with humid climates or climates with monsoon period showed a low increase of crop yield (India) or even reduced crop yield in China.

Distance and depth of pipes can also have influence on crop yield. The best effect on crop yield can be expected if pipes are on great depth and short distance. In systems where drains are relatively shallow and far apart, or the hydraulic transmissivity of the soil profile is low, the use of controlled drainage must be supervised and managed to avoid negative impacts on crop yields. However, in order to predict any future situations, long-term records of effects of controlled drainage on crop yields have to be determined because the short period of observation can contribute to the failure to detect effects of controlled drainage on yields.

3.8. Drainage Systems in the Czech Republic

The total area of agricultural land in the Czech Republic is 4.2 million hectares. Most of the agricultural land is covered with arable land where individual crops are rotated (3 million hectares), permanent cultures (978 thousand hectares), gardens (209 thousand hectares), vineyards (19 thousand hectares) and hop fields (10 thousand hectares) (Brozova and Uurman, 2019).

From beginning of 20th century till 1948., land was divided into smaller private properties. Later, land was collectivized and ownership was transferred to the state and management of large area. Management of drainage systems was supported by associations which were called ‘Water Cooperatives’. Members of these associations were landowners, farmers and engineers. Association's main purpose was development of water management by construction of drainage. The most agricultural drainage systems were built in 20th century, in the period before the World War I and after the World War II. In 1955, Agricultural Water Management Authority replaced the Association of Water Cooperatives and continued to work on improvement of water management in the Czech Republic. Since 1978, drainage systems in the Czech Republic cover 1,078,000 ha of land (around 25% of agricultural land), with mainly subsurface tile drainage systems (98%). In the Czech Republic, length of ditches is 12.185 km and they are built as open (length of 6835 km) or tube ditches (length 5350 km) (Kulhavý and Fučík 2015; Tlapáková et al, 2017)

Experimental and pilot research on constructions of controlled drainage was completed in the Czech Republic by issuing a provisional RD directive in 1978, then 1980 and finally a ROS directive in 1985. In the Czech Republic, conditions for controlled drainage were addressed by a number of authors and institutions, especially before 1989, starting with I. Radchenko, J. Němec, J. Fídler, F. Kulhavý, F. Mesarch and others. After 1989, change of political regime brought changes in land ownership organization where drainage systems were also included (Act No. 92/1991, Act No. 229/199) (Tlapáková, 2015). The new land owners were not fully aware of the existence of the drainage systems – they were legacy from the country and communistic political system regime.

3.8.1. Drainage System Challenges

Construction of controlled drainage systems has ceased along with the overall decline in amelioration activities in the Czech Republic. Drainage systems without investing and systematic maintenance affect lands around them, because their influence is not determined solely by their particular location. Nowadays, previously installed systems do not have function and new one have to be established in order to represent maintained drainage systems.

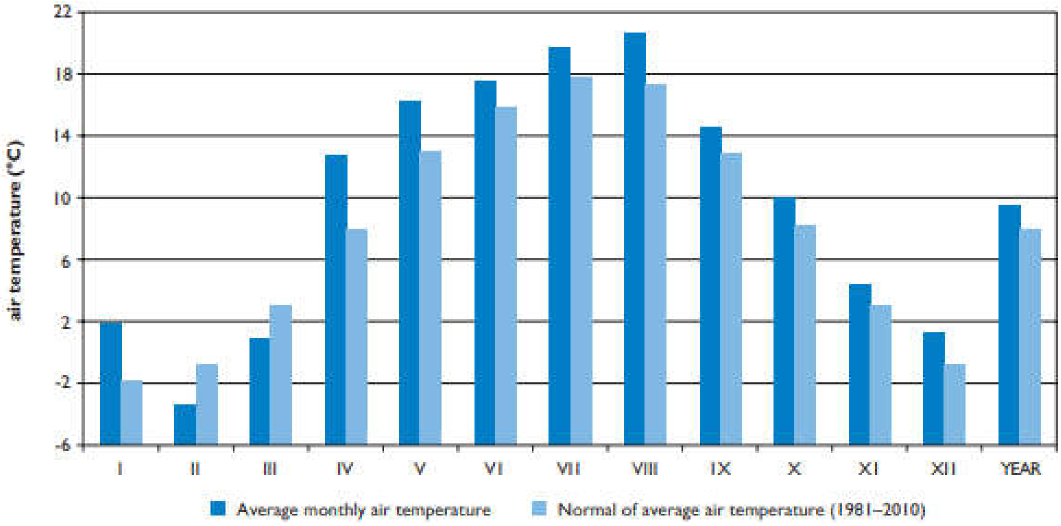
As a first step of rehabilitation of drainage systems in the Czech Republic, the current problems with drainage systems were single out by Kulhavy and Pelišek in 2017. Generally, drainage systems in the Czech Republic are in bad conditions due to:

- Inappropriate method of privatization of drainage structures trough history, which implies poor handover of structures without proper information and technical documents.
- Improper information was the consequence of inability to fulfill obligations demanded for drainage systems due to high fragmentation of ownership or professional inexperience of owners. Before, obligations were partially done by Agricultural Water Management Administration (Zemědělská vodohospodářská správa). Nowadays, obligations are fulfil on a very limited level by State Land Office (Státní pozemkový úřad).
- There is no institution to guarantee the integrity of the records. In 2004 the administration of subsidies started to use the geographic information system Land Registry-LPIS (Land Parcel Identification System), whose records the agricultural land used. The LPIS serves for various purposes such as verification of the information given in applications for grants in agriculture or as a register of organic farming or of environmental data. However, representation of data done by the LPIS can be considered as incomplete or even incorrect.
- Lack of legislative and professional obstacles which lead to non protection and non investment in drainage structures and reduction of importance and potential of systems.
- Non existence of a comprehensive model, which can define the contribution of drainage systems to sustainable environment.

As mentioned above, controlled drainage systems were built and tested before on areas of Bohemia and Moravia, on locations: Starý Kolín, Kolesa-Vápno, Bulhary-Přítluky, Lehota, Živanice and others. Additionally, there is necessity to revise the nationwide amelioration database, to complete the registration of drainage systems found in the Czech Republic (Tlapakova, 2017).

3.8.2. Reasons & Plans for Rehabilitation of Drainage Systems

The Czech Republic is one of many countries in Europe which will experience significant climate change effects. Climate changes have already become visible in the increase of the mean temperature for 0.69°C in the past 100 years. Variations of temperatures in the summer are 0.36°C and for the winter 0.93°C. These values may be higher at individual stations (Brazdil and Kirchner, 2007).



Graph 1: Comparison of average monthly temperature in 2018 and period 1981-2010

Source: Ministry of Agriculture of the CR, 2018

In 2015, annual mean air temperature of 9.4 °C exceeded the value of the long term average (1961–1990) by 1.9 °C and it was the ninth year with positive variation exceeding 1 °C and with 2014 it has been the warmest year in the more than last 50 years (Ministry of Agriculture and Environment of the CR, 2015). In order to reduce the climate change effects, the Czech Government issued a Resolution No. 620/2015-

Preparation of Measures Aimed at Mitigating Negative Effects of Drought and Lack of Waters. Due to Resolution, the Ministry of the Agriculture intensively started to create a concept which will provide protection against the consequences of drought or floods. The Ministry of Agriculture created 12 subsidy programs which will be implemented in 3 stages (2016–2021, 2022–2027 and 2027–2033). One of the programs supports reconstruction, reparation and modernization of the major drainage facilities. The main goal is the rehabilitation of existing controlled drainage, to contribute to an effective approach in decreasing diffuse pollution sources from tile-drained agricultural watersheds. Application of the CD will be achieved with a simple modification of existing drainages by inserting risers on pipes or drainage outlets. Expectations out of CD are new technical and methodological approaches and tools for regulations and reduction of runoff, pollution and sustainable farming. Furthermore, the main aim of the thesis is to represent current hydropedological situation in Kolesa-Vapno as one of the locations with installed controlled drainage. Hydropedological situation is expressed through analysis of the important parameters, which are the result of hydropedological survey.

4. Materials and Methods

The main method used for testing suitability of area in order to install, or in this case renew, a controlled drainage system is hydropedological survey that includes field and laboratory practices.

4.1. Hydropedological Survey

Hydrological part of survey includes analysis of hydrological parameters of surface water such as precipitation, evaporation, evapotranspiration, surface runoff, regime of sediments, the qualitative and quantitative characteristics of surface water or groundwater such as levels and movement of groundwater, humidity of the zone, sinking or infiltration of surface water, drainage rate, chemical composition of drained groundwater.

Survey for soil characteristics implies on grain size and aggregate analyses, determination of consistency characteristics (plastic and liquid limit), physical analysis of samples, retention of soil water or chemical analysis of pH, $CaCO_3$, Fe_2O_3, humus content, sorption capacity and sorption saturation complex, content of nutrients and microelements and other as needed analyzes (Burt, 2011).

4.1.1. Case Study Area Kolesa-Vapno

Case study area is located near two small villages Kolesa and Vapno in Pardubice Region at 240 m a.l.s. Controlled drainage in Kolesa-Vapno was installed between 1980 and 1982. at two objects (numbers 15 and 17). Type of constructed drainage system is subsurface drainage built in 1980’s and made with PVC pipes and main reservoir of water is the Strašovsky fishpond.

In order to represent the current situation, initial hydropedological survey took place on 23rd June, 2020 at object 15. The samples were taken from the field. During observation, the field was covered with water because of the earlier precipitation, so the soil was either near saturation or completely saturated with water.

Taken samples were brought to a laboratory, where further experiments were conducted. The data obtained from field and laboratory experiments was interpreted through series of calculations and graphs.

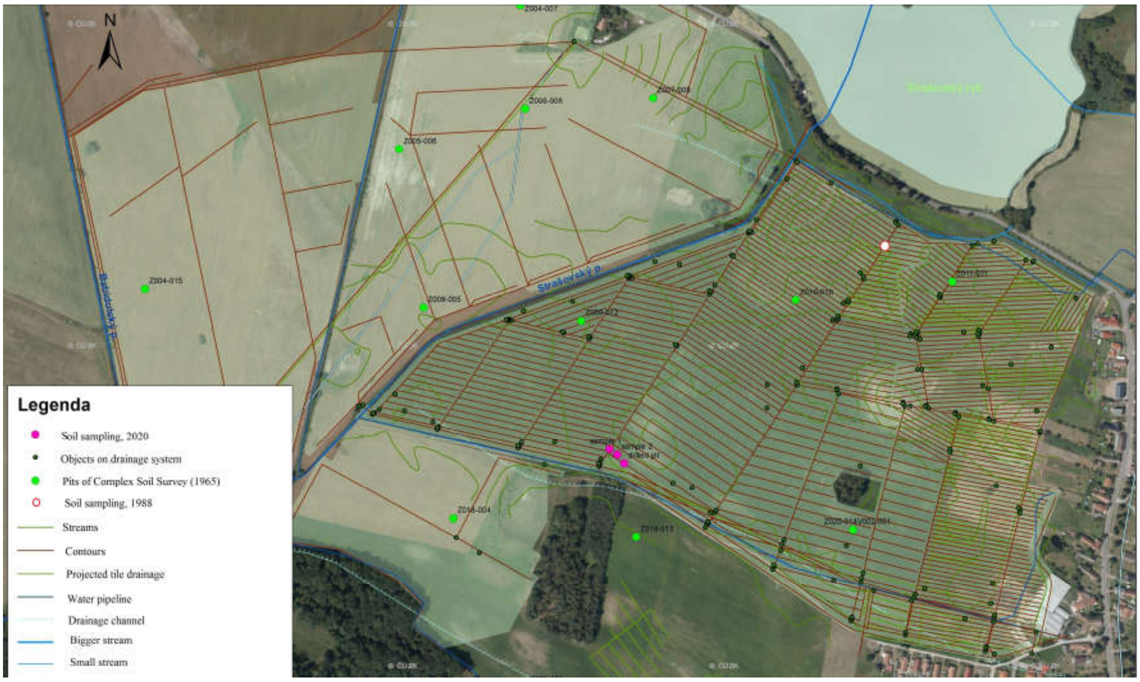


Figure 5: Object '15'

Source: VUPMOZ, Z. Kulhavy

4.1.2. Field Work in Kolesa-Vapno

Soil sampling included disturbed and undisturbed soil samples.

- Undisturbed samples were taken with to as Kopecky rings (100 cm^3 and 250 cm^3)

- Disturbed samples were taken by using auger where soil profile was created with 150 cm depth.

4.1.2.1. Undisturbed Soil Samples

The undisturbed soil sample was taken out for testing the properties in a laboratory, without disturbing its structure, texture, density, natural water content and stress condition.

Six undisturbed samples were taken: three in 100 cm^3 Kopecky rings and three in 250 cm^3 Kopecky rings at depth 0-15cm. Taken samples were marked as near the profile, point 1 and point 2 (further from the profile).

4.1.2.2. Disturbed Soil Samples

Disturbed soil samples were taken by auger. The procedure started with drilling a borehole that was bored into the soil to a depth of 150 cm. Samples were placed on plastic wrap, taking into consideration the depth level of previous excavation.

Figure 6: Soil profile.

From the mentioned samples was formed soil profile of 150 cm depth where the soil characteristics such as color, texture, type, humus, concretions, plasticity, adhesion, presence of Fe^{2+} or Fe^{3+} were shown. Later, borehole characteristics were taken in order to calculate saturated hydraulic conductivity. This method is called auger hole method and it is fast and reliable. The borehole characteristics which were taken from the field were radius of the borehole, the first registration of the groundwater, groundwater level in a steady state, thickness of water bearing layer, the final groundwater after the removal, and impermeable layer.

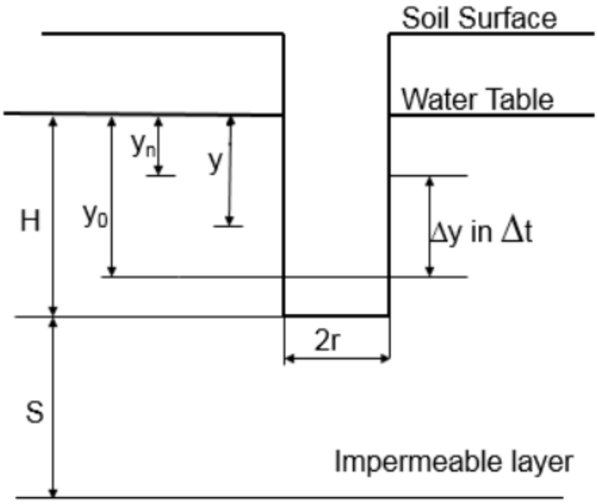


Figure 7: Experimental setup of auger hole method.

Source: (Mohsenipour and Shadid, 2016).

Borehole characteristics were used as parameters to calculate saturated hydraulic conductivity, by using Kirkham and Van Bavel formula.

Auger hole method does not represent suitable method for strongly layered soils or for soils with irregular porespace distribution (Mohsenipour and Shadid, 2016).

4.1.3. Determination of Parameters in Laboratory

The undisturbed samples collected at the site were taken to the laboratory, weighted and placed in oven at 105 °C for 24 hours. Undisturbed soil samples were used for water content measurements (100cm^3 Kopecky rings) and saturated hydraulic conductivity measurements by KSAT device (250cm^3 Kopecky rings). Surface samples were tested with water drop penetration time (WDPT) test for their water repellency in two-particle size below 0.25 mm and 2 mm. The WDPT test consists of placing a drop of water on the soil surface and measuring the time until complete penetration. None of the fractions in the sample showed water repellency.

Disturbed samples in laboratory were placed on a filter paper, so the stones and roots could be easily removed. Later, samples were dried at 55^{o}C, grinded, and filtered through 2 mm mesh size for determination of particle size distribution and particle density analysis.

After the determination of saturated hydraulic conductivity by KSAT was done, the three samples (250 cm^3 Kopecky rings) were placed with disturbed samples for determination of particle size distribution, in order to make a closer relation to results of the saturated hydraulic conductivity and particle size distribution.

4.1.3.1. Determination of Hydraulic Conductivity (K)

Hydraulic conductivity is defined as the volume of water that flows through a unit cross-section of soil per unit time, and is marked with a symbol K. Hydraulic conductivity can be measured in saturated and un-saturated zones.

According to the Darcy's Law in the saturated flow conditions, the velocity of water flow in the medium is directly proportional to the hydraulic gradient. The coefficient of this direct proportionality is called saturated hydraulic conductivity, which is expressed by units of velocity.

The Darcy's Law generally is given:

$$\mathbf{Q = -KiA}$$

Q is discharge rate [L^3T^{-1}], K is the hydraulic conductivity [$L.T^1$], i is the hydraulic gradient [$L.L^{-1}$], and A is the cross-section of soil sample [L^2]. Negative sign in a right part of equation marks the flow, which is running down.

The value of hydraulic conductivity varies due to different shape, size, distribution of the pores, viscosity and density of water and the temperature of soil. Hydraulic conductivity, as a parameter, has the most important role in activities such as water resources development, planning and management or environmental protection. Also, saturated hydraulic conductivity is one of the most significant parameters, which have effect on salt, pesticide, nutrient leaching, movement of pollution, water infiltration, and runoff (Pérez-Lucas et al, 2018)

4.1.3.1.1 Determination of Saturated Hydraulic Conductivity by Kirkham and Van Bavel Formula

Recorded borehole characteristics were used to calculate saturated hydraulic conductivity with Kirkham and Van Bavel formula from 1948.

$$K = 864 \cdot C \frac{\Delta y}{\Delta t}$$

Where calculation of is done by formula C = 0,617 r / (S H)

Interpolation of geometrical characteristic S can be interpolated with acceptable accuracy with use of Cisler's nomogram (Cisler, 1967), but the following values have to be calculated first:

h = H - y, h/H, r/H in order to use nomogram in a proper way

H is stable GW level

r is borehole radius

y is GW level during the rise rate measurement

4.1.3.1.2 Determination of saturated hydraulic conductivity by KSAT

Three undisturbed samples (250 cm^3) were taken at the field for measurement of saturated hydraulic conductivity by KSAT. It is a device (i.e. automated setup) manufactured by METER Group Inc., USA. KSAT is used for determination of saturated hydraulic conductivity in the lab, connected to the computer, which reads and uses Darcy's equation, to calculate saturated hydraulic conductivity. The pores of the porous plate must be completely filled with water before being placed on the soil sample. Observation of a complete saturation of the porous plate is possible when sample does not float in water, but settles. The device has ability to use the falling head (automated) and constant head (non-automated) methods on a soil core.

The falling head test is a common laboratory testing method used to determine the permeability of fine-grained soils with intermediate and low permeability such as silts and clays.

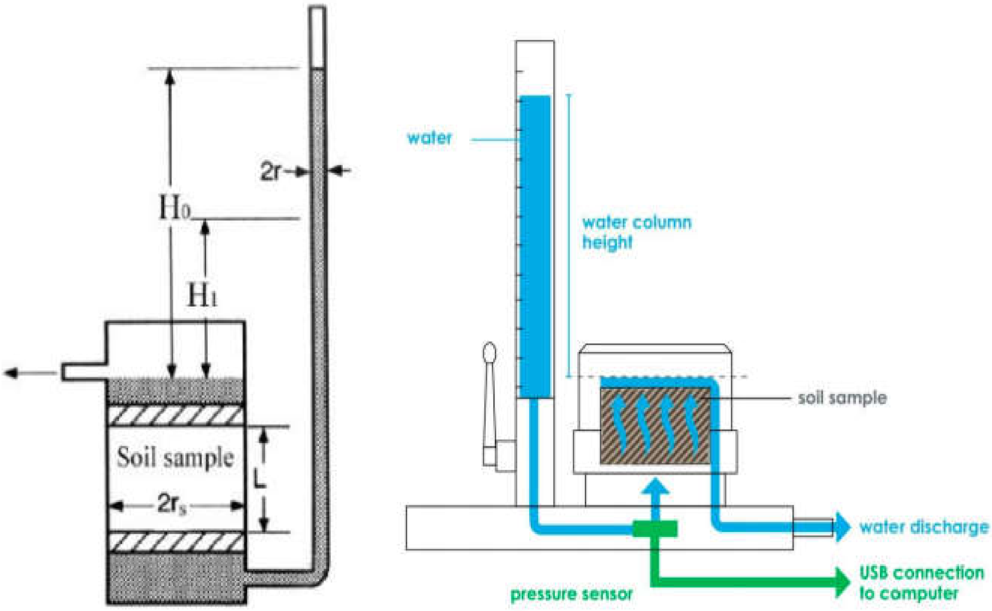


Figure 8: Principles of KSAT.

Source: Meter Environment, n.d.

4.1.3.2. Determination of Water Content and Bulk Density

Soil water content is expressed as a gravimetric unit (i.e. the mass of water per mass of dry soil) or volumetric water content. It is measured by weighing soil samples from the field (mass of wet sample), drying the sample to remove the water (on 105 °C), and then weighing the dried soil (mass of dry sample). The bulk density is the weight of dry soil divided by the total soil volume.

4.1.3.3. Determination of Particle Size Distribution

Particle size distribution (PSD) shows the relationship between the particle size and the concentration (Jonasz and Fournier, 2007). The PSD is used to classify soils for engineering or agricultural purposes, because size of particles can express different parameters such as water holding capacity, movement of water and nutrients or other components trough soil, drainage properties, root development (ASTM International, 2014).

An analysis of PSD can be performed using a variety of techniques. The most common method for determination of PSD is the hydrometer method. This method is based on Stokes' law, which states that particles based on the size (clay <0.002 mm, silt 0.002-0.5 mm and sand 0.05-2 mm) will have different fall out of suspension at different rates over time.

A dispersing solution was prepared by mixing 50 grams of sodium hexametaphosphate ($Na_3(PO_4)_6$) with one liter of distilled water. The solution was stirred and shaken until the dispersing solution has completely disappeared.

The analysis was done as follows:

1. Approximately 50 grams of dried, sieved soil was weighted and poured into a large container, which contained dispersing solution;

2. The mixture was prepared in 2:1 ratio; 100 milliliters of dispersion solution was mixed with 50 milliliters of distilled water inside of a beaker.
3. Solution with soil was shaken in electric mixer for 10 minutes to make sure there was no soil left at the bottom of the beaker, because no soil sample was allowed to be lost. Special attention was needed when mixer was used, in order to prevent any possibility of sample loss.
4. The distance between the base and 500 ml mark on the cylinder was measured with a ruler. The suspension with soil was placed into sedimentation cylinder. Distilled water was added in order to fill the cylinder up to 1000 ml mark.
5. Using a stopwatch, timing of experiment was started immediately, and so was measuring of the temperature.
6. The hydrometer was carefully lowered into the cylinder and left to float in the soil suspension. The hydrometer needed to be carefully made steady and stabilized to prevent its further motion.
7. After reading has been conducted, the hydrometer was removed from the cylinder, rinsed, dried and put gently on a safe place. As there was one hydrometer per sample, a special attention was needed not to mix different hydrometers with different samples.
8. The readings have been conducted at 8 intervals during the first day of the experiment and repeated after 24 and 48 hours. The time and temperature have been recorded with every reading as well.
9. At the end of the experiment, the soil suspension was discarded and equipment was carefully cleaned.

According to exact percentage of clay, silt and sand, determination of textural classes was done based on soil textural triangle defined by USDA. Soil texture triangle is used as tool for visualization and better understanding of soil types, more precisely, a diagram, which shows how each of these 12 textures is classified based on the percent of sand, silt, and clay in each sample.

4.1.4. Determination of Soil Particle Density

Particle density of soil is measurement of a soil mass sample in a given volume of particles. It includes the volume of mineral and organic portion of soil, together with space occupied by water and air. Soil particle density of soil sample has been determined by employing water pycnometer method.

The procedure was conducted as follows:

1. A scale was used to obtain approximately 15 grams of air-dried soil. The sample was then transferred to pycnometer[4]. It was important to mix soil before weighing and transferring to pycnometer in order to homogenize it, as well as to clean the funnel and spoon between samples, in order to prevent mixing of the samples.
2. Pycnometers with soil samples were transferred to oven and heated at 105 °C for 2 hours. Oven-dried samples with pycnometer were weighted after this time.
3. A small amount of distilled water was added to the soil. This was done very carefully, by slow addition of distilled water on walls of pycnometer, in order to prevent destroying of micropores, as well as to prevent any soil sample loss from pycnometer.
4. Samples were placed in desiccator, with lid on top, to prevent any loss from samples due to high pressure inside the desiccator. The desiccation process took 2 hours.
5. Pycnometers were taken out, and degassed water was added.
6. The desiccator was closed, and vacuum was switched on for one hour.
7. The pycnometers were taken out from desiccator, filled with degassed distilled water and then transferred to tempering bath.
8. After tempering, samples were measure/weighted again.
9. At the end of the experiment, the soil suspension was discarded and equipment was carefully cleaned.

---

[4] Pycnometer is a glass flask fitted with a ground glass stopper that is pierced lengthwise by a capillary opening.

5. Results

After completing the fieldwork, collecting samples, and conducting laboratory-based tests and measurements, the following section will focus on presentation of the obtained results. It is divided into several sub-sections, following the above outlined structure of the thesis and the parameters used.

5.1. Water Content

Table 3. (below) outlines the obtained results from samples Kopecky rings (100 cm^3) of the saturated water content, including dry bulk density and particle density.

Table 3: Results of the saturated water content, dry bulk density and particle density.

	Saturated water content by mass (%)	Saturated water content by volume (%)	Dry bulk density (g/cm^3)	Particle density (g/cm^3)
Profile	31.1	42.372	1.36	2.56
Point 1	35.9	46.564	1.30	2.53
Point 2	38.0	48.332	1.27	2.56

5.2. Soil Profile Characteristics by Auger Hole

Table 4. (below) summaries the key characteristics of the soil profile.

Table 4: Characteristics of the soil profile.

Depth (cm)	Color	Humus	Conditions	Disintegration	Plasticity	Adhesion	Mica	Fe2+
0-30	Black	Yes	Moist and soft	Easy	No	Mild	Little	No
30-45	Brown/ black	Some	Moist, dense and soft	Medium	No	Mild	Little	No
45-70	Brown	No	Wet, dense, rigid	Difficult	No	Mild	Little	Yes
70-90	Grey brown	No	Wet, dense, rigid	Difficult	No		Medium	No

Table 5. (below) sketches recorded borehole characteristics on the field were used for calculation of saturated hydraulic conductivity.

Table 5: Recorded borehole characteristics on the field

Observation	Value	Unit
Borehole depth	150	cm
Radius of the borehole	3.5	cm
First registration of the GW	65	cm
GW level in steady state	45	cm
Thickness of water bearing layer	95	cm
Final GW after removal	91	cm
Impermeable layer	Not known	Not known

After measurement of the steady state, the groundwater is pumped out from the hole and registered and then measurement of the rate of the raise was done three times with eleven readings each. Figure 2. (below) recaps the obtained results.

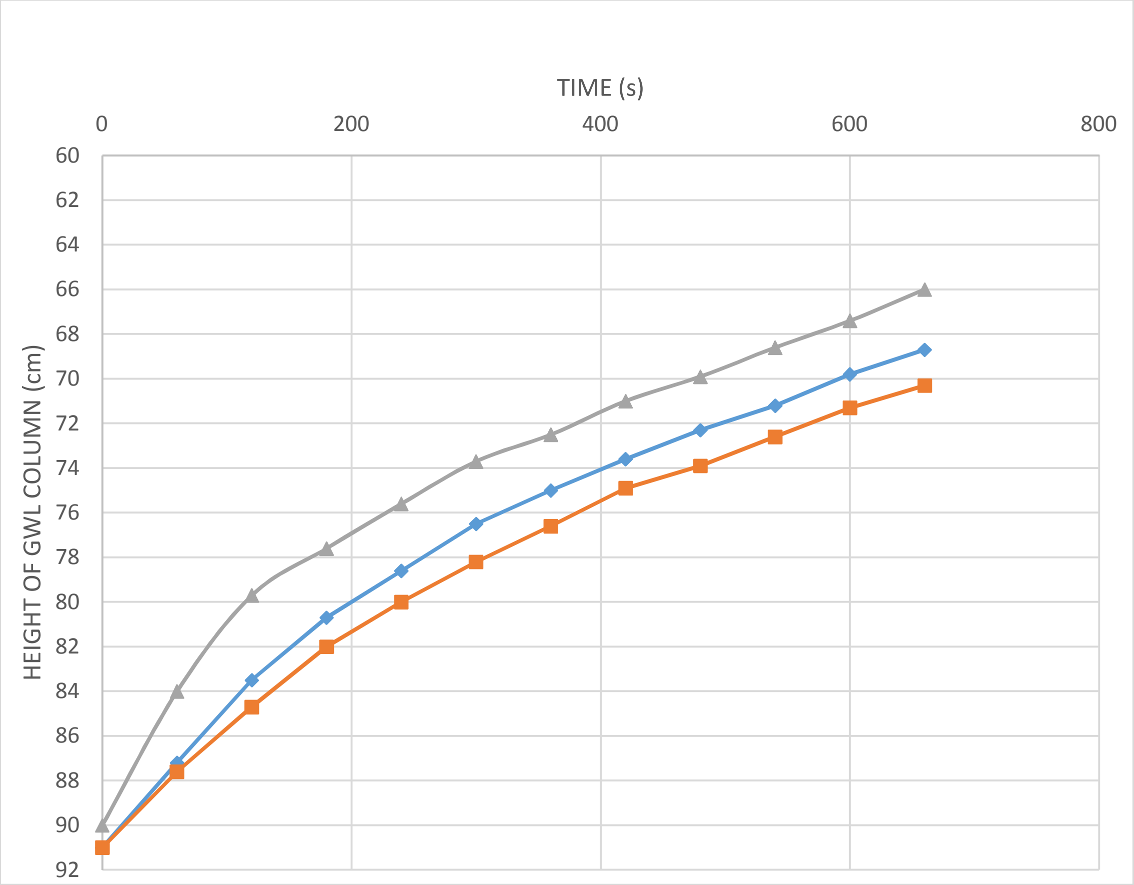


Figure 2: Rising of GWL (3 measurements).

5.2.1.1. Saturated Hydraulic Conductivity by Kirkham and Van Bavel Formula

The Kirkham and Van Bavel formula was used to calculate saturated hydraulic conductivity, and the results are presented in the table 6.

Table 6: Results of saturated hydraulic conductivity (cm/day).

Observation	H	yter	y0	yn	y	R	Δ y	Δ t	C	K(cm/day)
1	105	45	45	21	33	3.5	24	660	0.05876	16.2
2	105	45	46	23.7	34.8	3.5	22.3	660	0.05876	15
3	105	45	46	25.3	35.6	3.5	20.7	661	0.05876	13.9
Average						15.03				
Standard Deviation						1.1503				
Variance						1.3233				

5.2.2. Top Soil Saturated Hydraulic Conductivity by KSAT

Saturated hydraulic conductivity of the samples in Kopecky rings (250cm^3) determined by KSAT is outlined in the Table 7.

Three replicates were done for each sample.

Table 7: Saturated hydraulic conductivity measured by KSAT.

Replicates	Ks (sample Next to the Profile) (cm/day)	Ks (sample Point 1) (cm/day)	Ks (sample Point 2) (cm/day)
1	50	1	10
2	47	1	6
3	46	1	6
Average (cm/day)	47.6	1	7.3
Average (m/day)	0.476	0.01	0.073
Average (m/s)	5.50926e-6	1.1574e-7	8.4491e-7

5.3. Particle Size Distribution by Hydrometer

Particle size distribution of samples with replicates is outlined in the tables below (exact percentage of clay, silt and sand) and graphs.

5.3.1. Particle Size Distribution, Samples from Kopecky Rings (250 cm^3)

Table 8: Particle size distribution of Kopecky's rings (250 cm^3 and depth 0-15 cm)

Points	Clay (%)	Silt (%)	Sand (%)	Soil type (by USDA)
Near the profile	15	7	78	Sandy loam
	15	7	78	Sandy loam
	16	6	78	Sandy loam
Point 1	20	8	72	Sandy clay loam
	20	8	72	Sandy clay loam
	20	8	72	Sandy clay loam
Point 2	18	7	75	Sandy loam
	18	7	75	Sandy loam
	18	8	74	Sandy loam

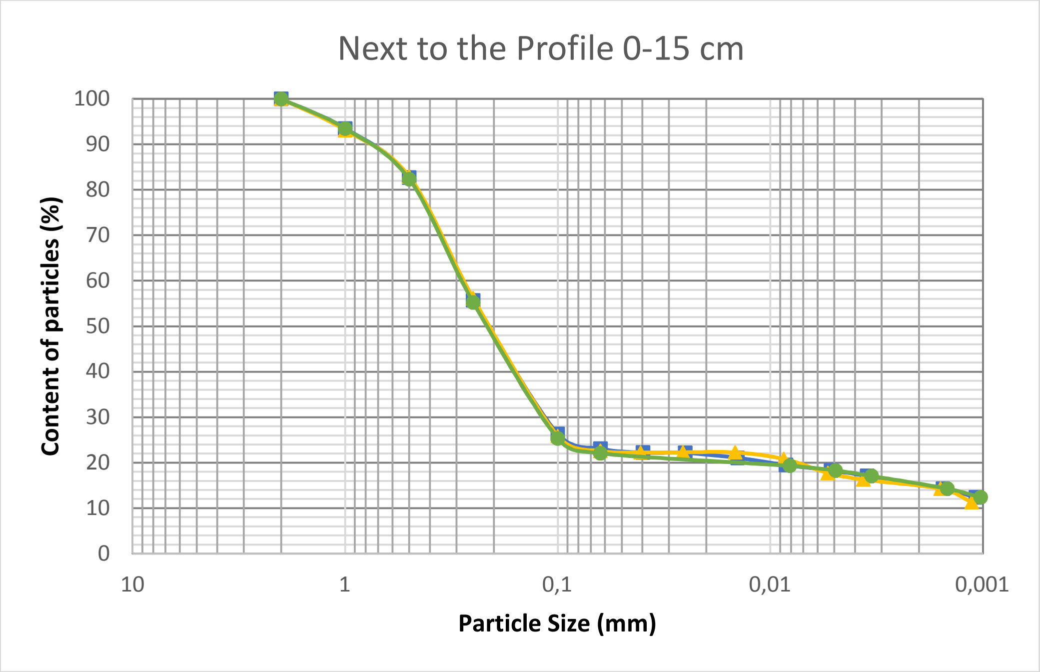


Figure 9: PSD curve, sample next to profile, depth 0-15.

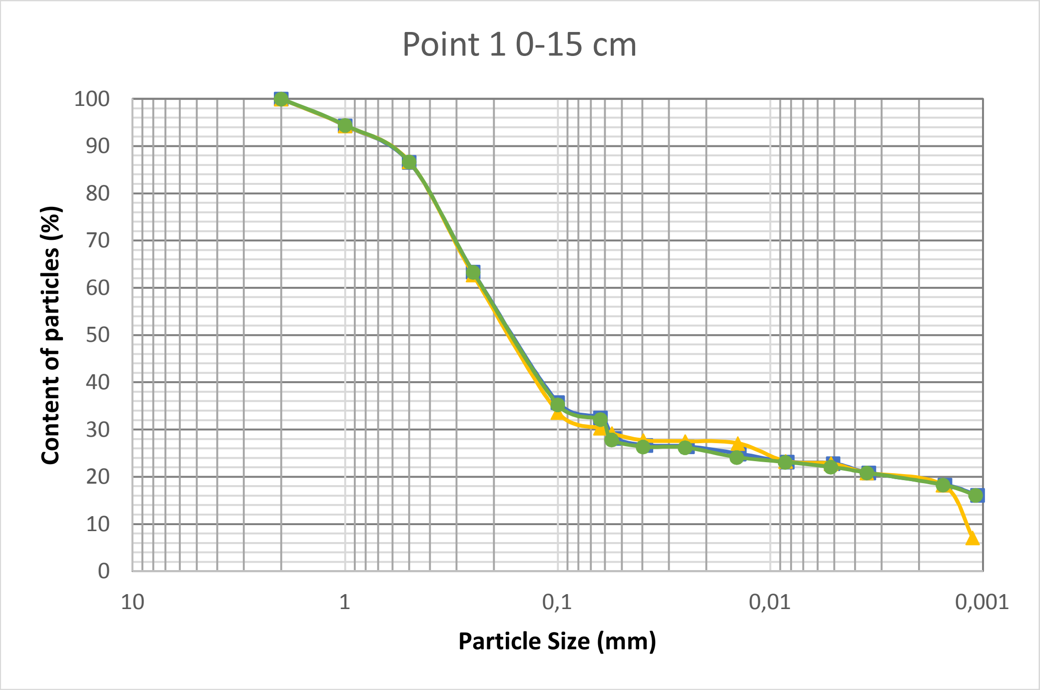


Figure 10: PSD curve, sample point 1, depth 0-15 cm.

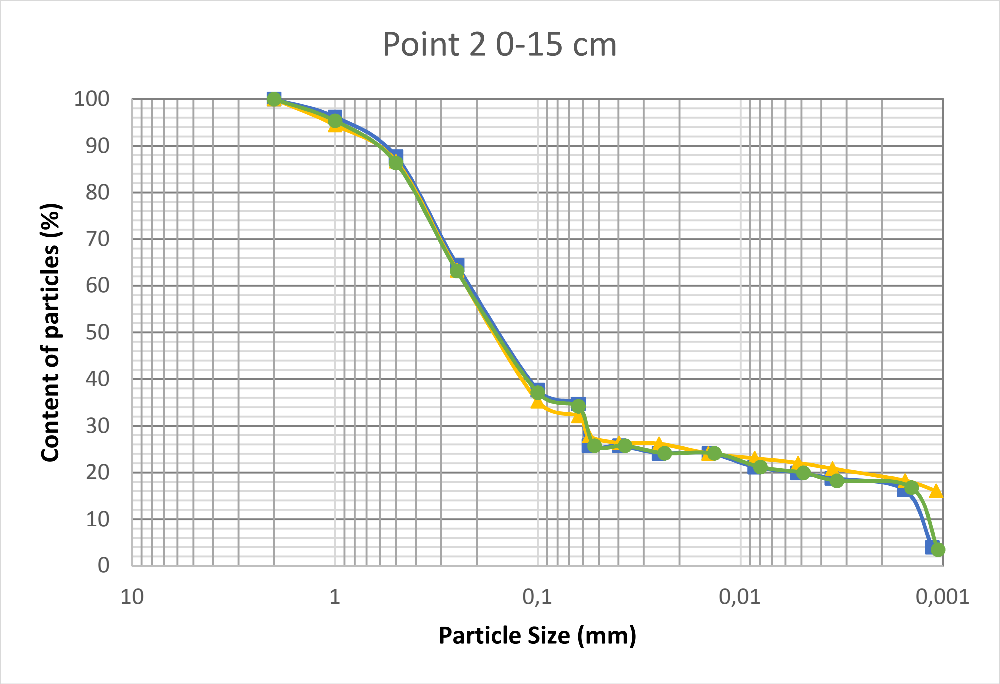


Figure 11: PSD curve, sample point 2, depth 0-15 cm.

5.3.2. Particle Size Distribution of Profile, depth 0-30 cm

Table 9: Particle size distribution, depth 0-30 cm

Replicates	Clay (%)	Silt (%)	Sand (%)	Soil type (by USDA)
First (blue)	16	9	75	Sandy loam
Second (yellow)	18	6	76	Sandy loam
Third (green)	18	7	75	Sandy loam

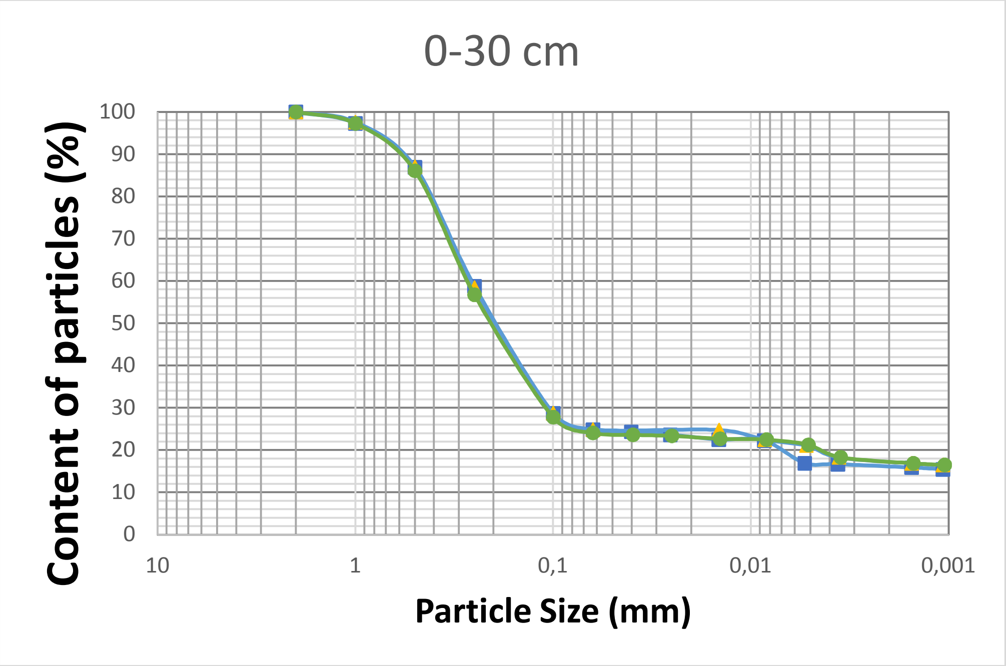


Figure 12: PSD curve, depth 0-30 cm

5.3.3. Particle Size Distribution from Depth 30-45 cm

Table 10: Particle size distribution, depth 30-45 cm.

Replicates	Clay (%)	Silt (%)	Sand (%)	Soil type (by USDA)
First (blue)	15	5	80	Sandy loam
Second (yellow)	15	5	80	Sandy loam
Third (green)	15	5	80	Sandy loam

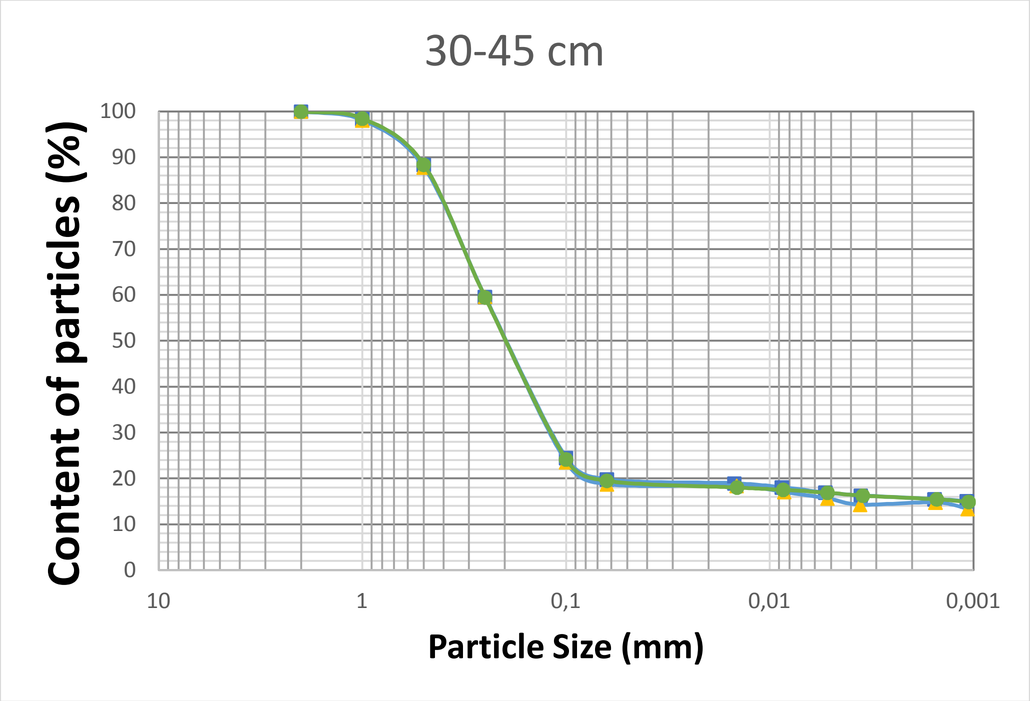


Figure 13: PSD curve, depth 30-45 cm.

5.3.4. Particle Size Distribution from Depth 45-70 cm

Table 11: Particle size distribution, depth 45-70 cm.

Replicates	Clay (%)	Silt (%)	Sand (%)	Soil type (by USDA)
First (blue)	14	1	85	Loamy sand
Second (yellow)	13	2	85	Loamy sand
Third (green)	14	1	85	Loamy sand

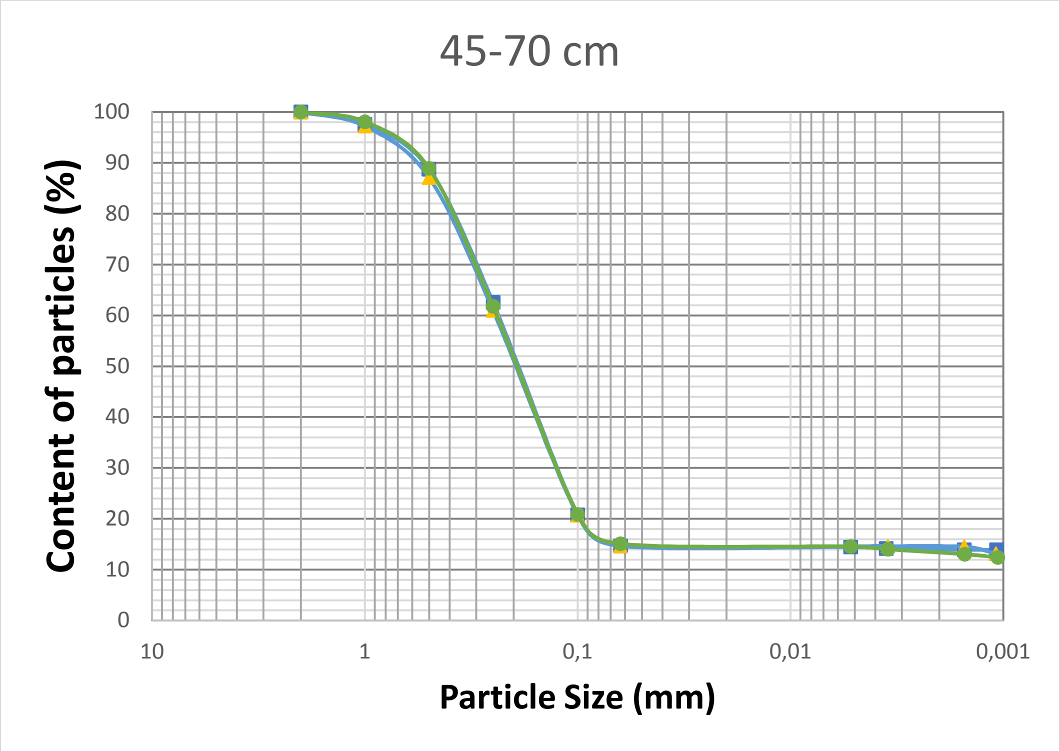


Figure 14: PSD curve, depth 45-70 cm.

5.3.5. Particle Size Distribution from Depth 70-90 cm

Table 12: Particle size distribution, depth 70-90 cm.

Replicates	Clay (%)	Silt (%)	Sand (%)	Soil type (by USDA)
First (blue)	11	1	88	Loamy sand
Second (yellow)	10	2	88	Loamy sand
Third (green)	10	1	89	Loamy sand

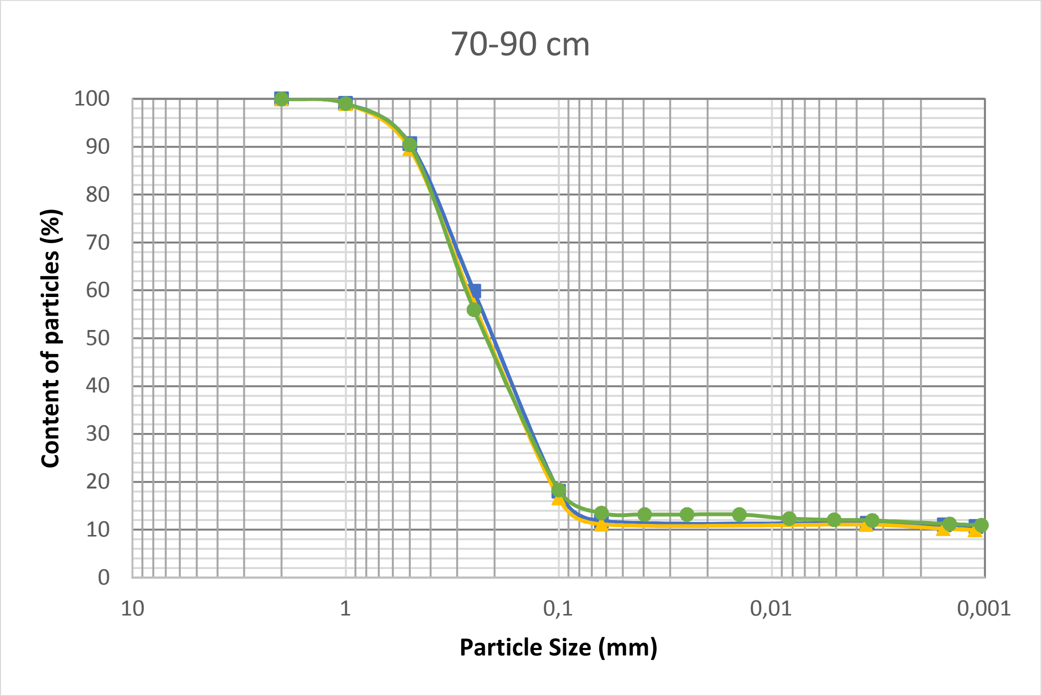


Figure 15: PSD curve, depth 70-90 cm.

5.3.6. Particle size distribution depth below 90 cm

Table 13: Particle size distribution, depth below 90 cm.

Replicates	Clay (%)	Silt (%)	Sand (%)	Soil type (by USDA)
First (blue)	3	5	92	Sand
Second (yellow)	2	6	92	Sand
Third (green)	4	3	93	Sand

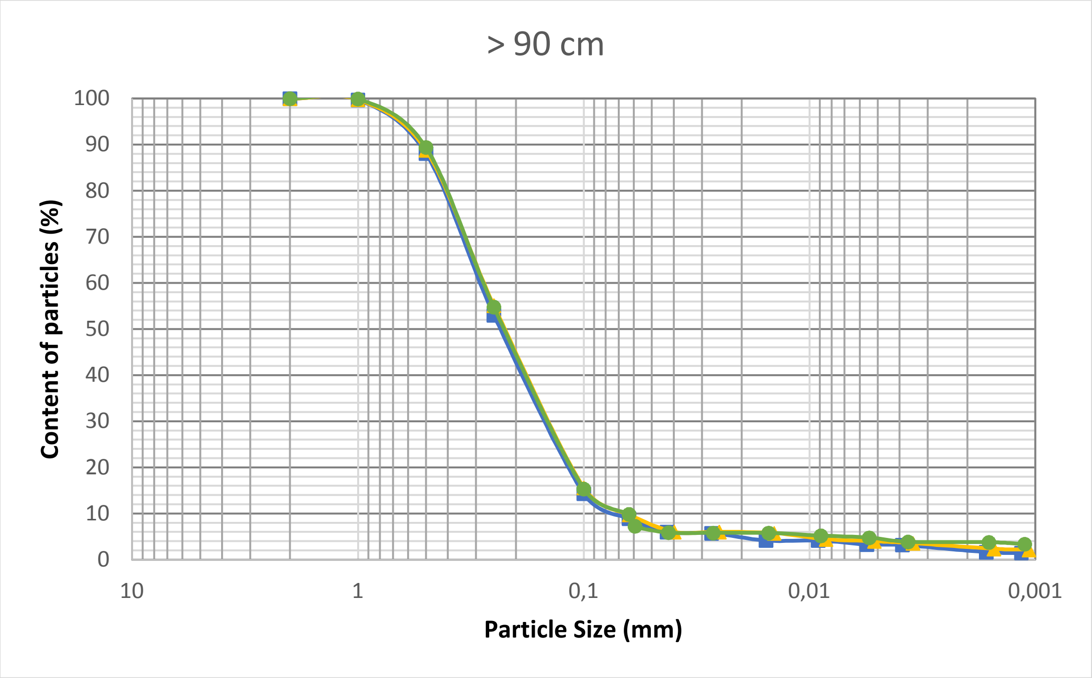


Figure 16: PSD curve, depth below 90 cm.

5.3.7. Textural Classes Based on PSD in a Soil Texture Triangle

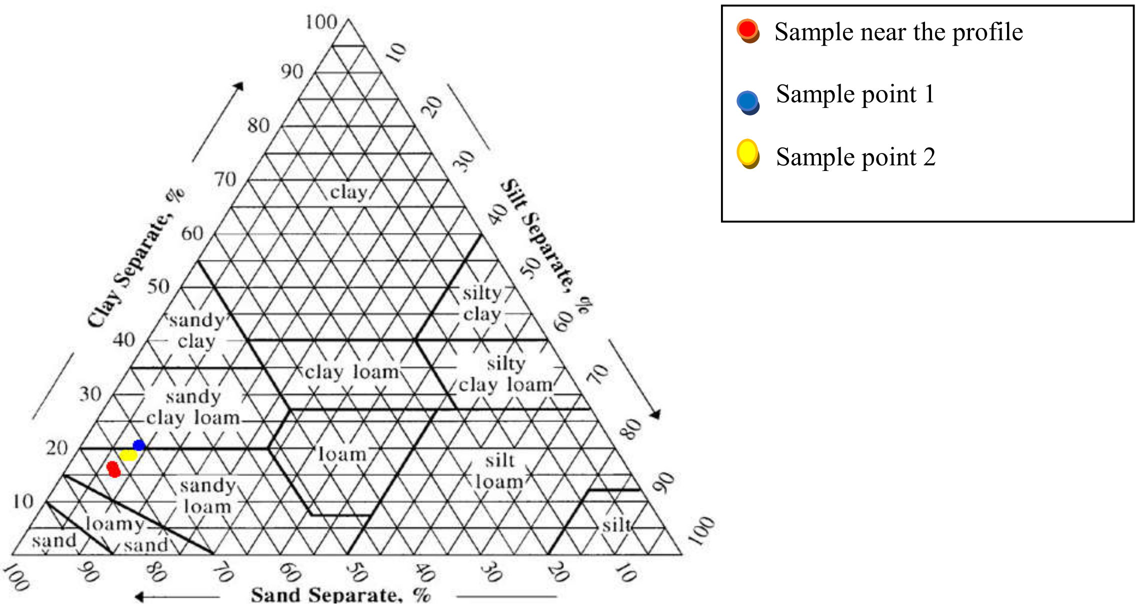


Figure 17: Textural classes based on USDA classification.

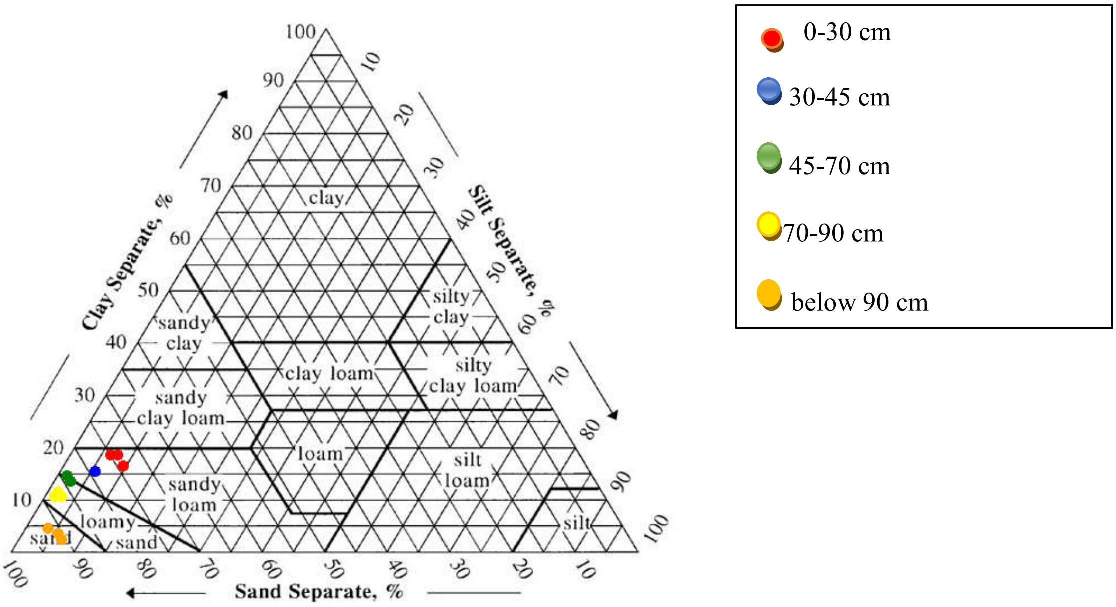


Figure 18: Textural classes based on USDA classification.

5.4. Particle Density

The following figure summarizes the particle density in topsoil samples and trough the profile.

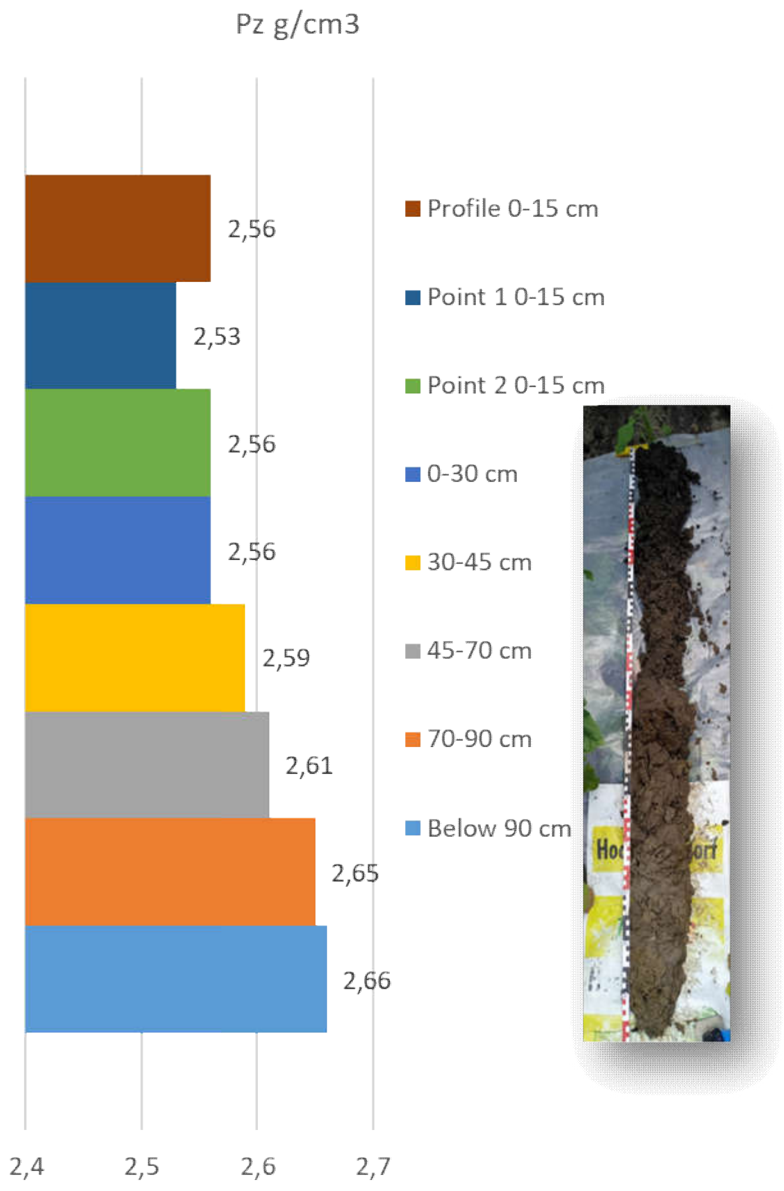


Figure 19: Results of particle density.

6. Discussion

After outlining all germane measurement procedures and the obtained results, based on the data collection and processing methods described above, this section discusses some of the most interesting findings and observations, pertinent to the research questions and hypotheses outlined at the very beginning of the thesis.

In order to grasp the current situation at the investigated site and to comprehend whether the CDS' functionality and the effects have significantly changed or been in any way affected by improper management in the past ~30 years, the data from last hydropedological survey were collected. The last recorded hydropedological survey before was done in June 1988, at object '15' by Kulhavy. It was evaluated from auger hole method (i.e. two boreholes) near Strašovsky fishpond (i.e. Strašovsky rybnik). Particle size distribution measurement was done in 1985 (two boreholes, depth 30, 50 and 70 cm) by Nalmestek[5]. A comparison of the two sets of data, collected by the thesis author in 2020, and by a group of researchers in 1985 and 1988, indeed showed some changes in the main observed parameters: particle size distribution and saturated hydraulic conductivity.

Determination of the soil texture was done on samples from the profile (different depths 0-30cm, 30-45 cm, 45-70 cm, 70-90 cm, below 90 cm) and samples from topsoil (Kopecky's rings, 250 cm^3, 0-15cm). Textural classes of the profile changed with the change of the depth. Determined textural class of soil layer (0-30 cm depth) is sandy loam. The content of clay and silt decrease with increasing depth of the profile. After depth of 45 cm, the content of silt was really low (1-2%). However, the content of clay in deeper layers (30-70cm) was higher than in 1988, almost by three times. The content of sand particles gradually increase (below 90 cm is more than 90% of sand particles).

PSD curve of data from 1985. showed higher content of clay particles up to 13%. However, clay content in deeper parts (30-70 cm) is higher in 2020.

---

[5] Nalmestek, Particle size distribution, sampled and measured in 1985, VUMOP.

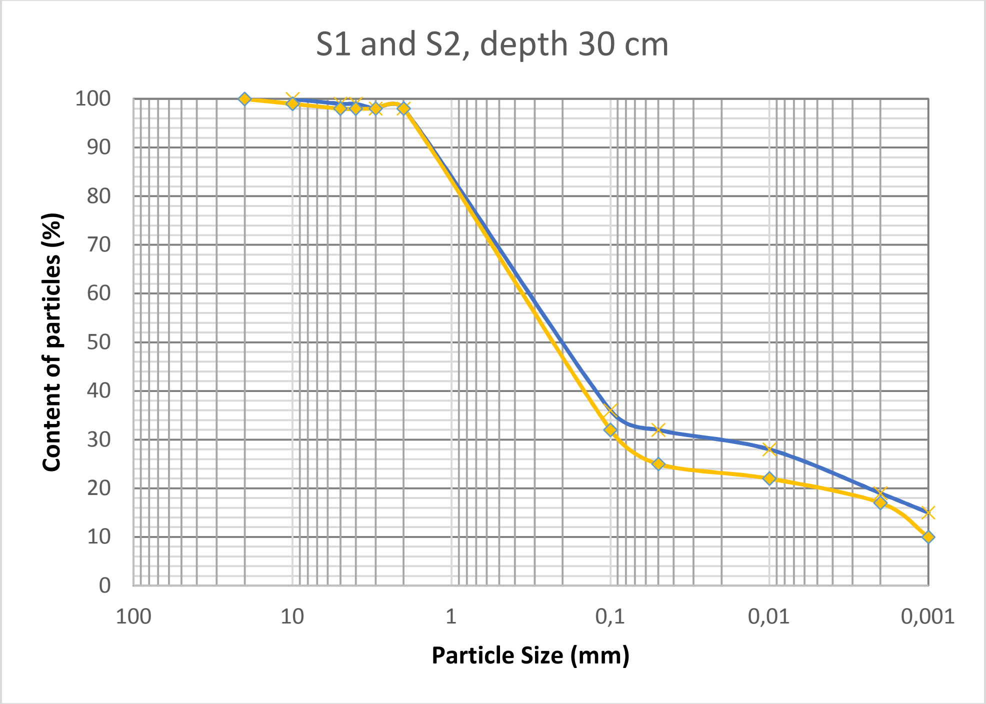


Figure 20: PSD curve data from 1988, points S1 (yellow) and S2 (blue), depth 30 cm.

Source: Namestek,1985

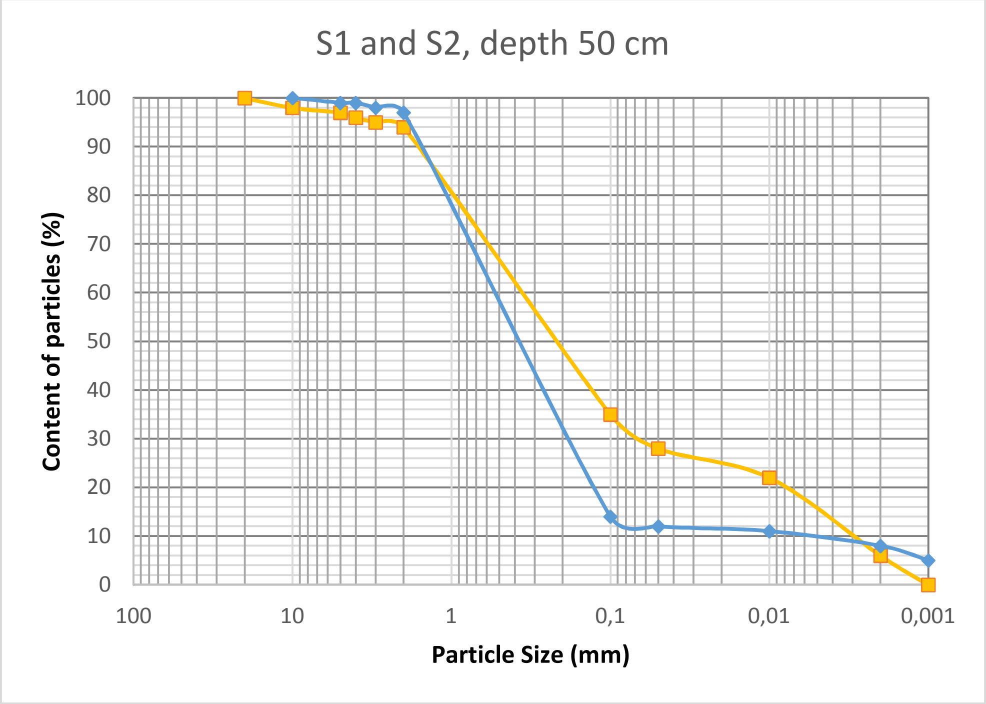


Figure 21: PSD curve, data from 1988, points S1 (yellow) and S2 (blue), depth 50 cm.

Source: Namestek, 1985

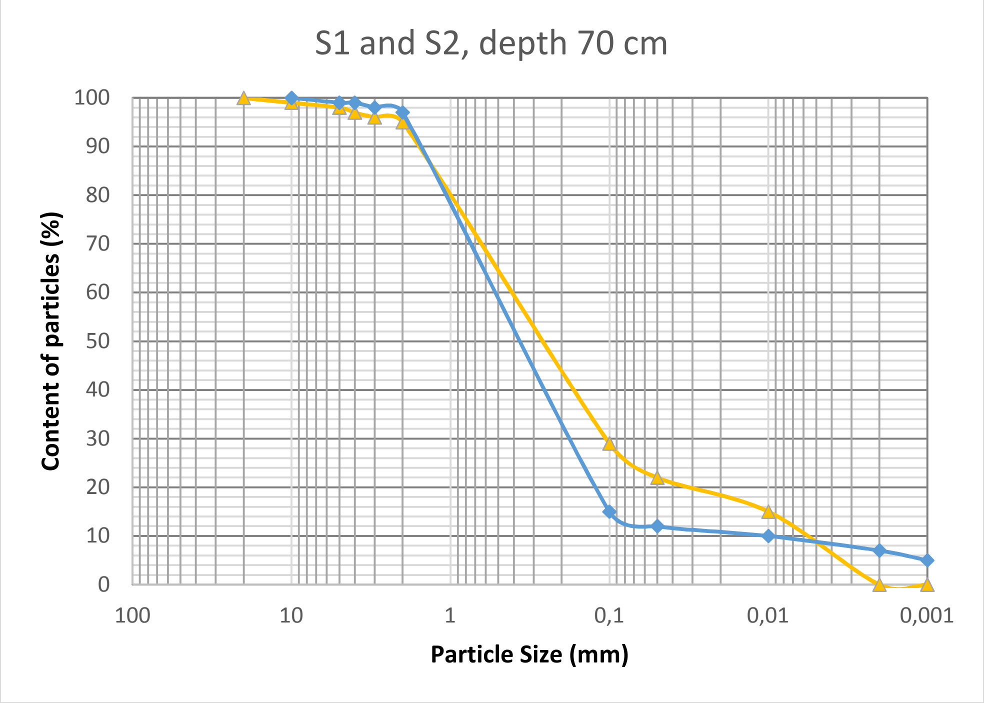


Figure 22: PSD curve, data from 1988, points S1 (yellow) and S2 (blue), depth 70 cm.

Source: Nalmestek, 1985

The samples from Kopecky rings also delineated some differences. The first sample, which was taken near the profile, had similar results to the profile. The content of the particles was similar to the profile depth (0-30cm). However, point 1 indicated different results, such as higher content of clay, and textural type sandy clay loam (~20% of clay). To express difference in clay content, a clay ratio was done, by calculating a total sand and silt over clay (cf. Chandra and De, 1976). The determined clay ratio in 1985 was between 2.92 and 4.36, while the measurements obtained in 2020 indicate that clay ratio varied between 4.55 and 5.25.

Mineral particles (sand, silt, clay) have higher densities compared to the organic matter. The change of particle density (2,56- 2,66 g/cm^3) through the profile was following the increase of the sand particles and decrease of organic matter.

The results of saturated hydraulic conductivity calculated by Kirkham and Bavel formula from auger hole method and KSAT also showed different results comparing with results from 1988. Values of Ks calculated by Kirkham and Bavel formula were 13.9, 15 and 16.2 cm/day (0.0000016, 0.0000015 and 0.00000187 m/s). The saturated hydraulic conductivity was calculated in 1988. on marked place (see figure 5), marked as S9 and S11 near fishpond by Kirkham and Bavel formula. The saturated hydraulic conductivity was measured six times in four days in both boreholes (12 measurements). The obtained results showed higher results in range of 27 and 156 cm/ day. The average saturated hydraulic conductivity of S9 and S11 hole is 63.56 cm/day 88.98 cm/day. The calculated standard deviation of S9 samples is 42.77 and for S11 is 50.20. The high value of the calculated standard deviation in both cases shows variability of results, which requires further research. It is worth mentioning that the tests in 1988 were done in very narrow auger holes with radius of only 1.25 cm. In order to properly calculate saturated hydraulic method with Kirkham and Bavel formula, some basic requirements need to be fulfill, and the diameter of auger should be between 3 and 7 cm (Báťková et al, 2013), which certainly indicates the need for further research. Generally, the lower values determined by Kirkaham and Bavel formula can be interpreted as a result of the long-term activities on arable land. Observed reduction of Ks on arable land, compared with natural vegetation and forests, can often occur as effect of tillage, which disrupts macropores, especially the faunal and root biopores (cf. Jarvis et al, 2013).

Samples Point 1 and 2 measured by KSAT showed lower hydraulic conductivity values. Reason for lower value can be due to higher content of clay (Point 2) or really low value of saturated hydraulic conductivity in sample Point 1 can be caused by compaction and clogging the pores due to stagnation of water. However, the surface hydraulic conductivity in the sample near the profile point was much higher than the values observed in auger-hole method. The hydraulic conductivity of this point was between 46-50 cm/day. Similar results can be partly explained by positive correlation of organic carbon and saturated hydraulic conductivity. The bulk density, soil organic carbon are considered as most important predictors for determination of Ks. Organic carbon improves soil structure and has positive correlation with Ks value. The bulk density was determined from the samples taken from topsoil. For textural class sandy loam, the ideal bulk density is smaller than 1.4 g/cm^3. The results of bulk density were between 1.27 g/cm^3 and 1.36 g/cm^3, which means they are suitable for plant growth.

The result of saturated hydraulic conductivity by KSAT, showed high variability and more measurements should be done in order to discuss differences in details.

Generally, the soil texture has slow changes with time. However, the change in content of particles can be observed due to the different processes. Soil erosion, within a long term, can cause serious loss of topsoil by decreasing soil compaction, organic matter and loss of soil structure. Soils with faster infiltration rates, higher levels of organic matter and improved soil structure have a greater resistance to erosion. The main components affected by erosion are change of organic matter levels and the soil structure.

According to the survey results, topsoil showed a reduced content of the clay, low organic matter and non-structure soil. Detected high contents of charcoal particles even below 30 cm can have effect on soil aggregation. High amounts of charcoal can be present due to stubble burning or presence of recalcitrant organic particles. The charcoal concentrations can increase even one year after burning and due to time charcoal is accumulated and mixed in the soil material (cf. Eckmeier et al, 2007). Recalcitrant organic particles are material resistant to decomposition and largely unavailable to microorganisms. These particles can disable soil aggregation by reducing microbal habitat, which is able to support soil aggregation. High rates of erosion can be caused by greater intensity and duration of a rainstorm. Raindrops can break down the soil aggregates and disperse the aggregate material. Due to the heavy rain, particles such fine sand, silt, clay and organic matter can be easily removed (Ritter, 2012). Due to climate change, rainstorm became often occurrence, in some area followed by floods of relatively small spatial extent and duration (Danhelka et al, 2009).

The installation of subsurface drainage systems has a significant effect on reduction of erosion in areas with high slope and subsurface drainage systems also showed positive results in decrease of the runoff and erosion in flat areas (Istok et al., 1985). However, due to lack of maintenance, the drainage systems can make unpredictable erosion due to improper drain of water. During the data collection field-work, the area was covered with water, after two days of heavy rain. The water content determined from samples (Kopecky rings 100cm^3) showed increased percentages 31.1%, 35% and 38% (m/m). Comparing with the survey results done in 1988, the highest detected water content during four days did not have such high values. An average percentage of water content at depth 0-10 cm was 26.8% and only one value was above 30% (32.4%). Water did not drain after two days, which can be partly attributed to improper management of the existing systems. Successful management of water table in controlled drainage requires a periodic monitoring of the water table, and depends on the weather and crop development stage. In order to develop a root system, water table will be between 0.5 and 0.75 m from the surface. Due to set of high level of water table, response of the water table to rainfall and control structure adjustments can have slow actions. In order to make expectation of water retention, every system requires time to analyze and discover the response patterns which have to be followed to lead and maintain system. (cf. Zimmer and Madramootoo, 2007.).

Zimmer and Madramootoo (2007) suggested proper monitoring with proposed time interval to reduce any negative impact of controlled drainage.

Table 14: Monitoring suggestions of parameters followed in applying controlled drainage.

Impacts	Parameters to monitor	Monitoring interval
Peak flows	Surface runoff, subsurface drain discharge, water levels in stream	1- hour intervals with automatic devices
Soil erosion	Sediment in surface runoff	Accumulation after rainstorm using sediment samplers
Nutrient losses	Nitrate, ammonium, phosphorus	Monthly, during the growing season
Pesticide losses	Pesticide concentration	Monthly, during the growing season

Nowadays, the most usable water management model is DRAINMOD. This model is considered is used to give site-specific recommendations for riser management. Recommendations for specific area are based on historic weather data, soils and specific drainage system conditions (Poole et al, 2018). Beside DRAINMOD, there are other models which are use as well such as SWAT or SWATDRAIN (Golmohammadi et al, 2016; Youssef et al, 2018).

7. Conclusion

In this day and age, countries are developing new methods and models to achieve sustainable water management. According to many successfully tested examples, the controlled drainage systems are considered as one of the successful ways to conserve and protect water resources. The main advantages of controlled drainage are: reduction of outflow, reduction of leaching of important nutrients such as nitrogen and phosphorus, reduction of salts, increased crop production. However, controlled drainage systems have to have specific conditions in nature in order to achieve their full potential. The optimal conditions are flat area slope gradient which not exceed 1%, a high permeability soil (> 0.5 m d^{-1}) or shallow groundwater table, and an impermeable layer 1-3 m below the surface in order to retain water on high position.

The Czech Republic tested and installed different types of control structures for application of controlled drainage in the 1980's, at various locations. Changes in political system in the early 1990's also led to changes in management of the drainage systems, which in some cases resulted in improper maintenance.

This thesis aims to contribute to an ongoing research in the field, by focusing on whether improper and insufficiently accurate use and maintenance of the controlled drainage systems, over a significant amount of time, can affect its overall functioning and feasibility. This is done by investigating the current hydropedological situation of a controlled drainage at Kolesa-Vapno site (Pardubice region), and by mapping the measurable and verifiable changes that occurred in the past 30 years. The potential changes were observed through analysis of several parameters, such as water content (gravimetric and volumetric), particle density, saturated hydraulic conductivity (Auger hole method and KSAT) and particle size distribution (Hydrometer method).

The collected samples and the results obtained through rigorous methodological measurements demonstrate that some changes occurred due to general erosion, climate change and improper maintenance of installed controlled drainage system. The tested parameters, such as water content, particle density, saturated hydraulic conductivity and particle size distribution served as indicators to illustrate the current situation in the field. The hypothesis H_1 was verified to a certain degree, as described below.

There are considerable changes in the current system's functionality and overall serviceability due to the improper maintenance, and they are noticeable in parameters such as water content, particle size distribution and saturated hydraulic conductivity. More specifically, the particle size distribution showed decrease of clay content, especially on the surface. Saturated hydraulic conductivity calculated by Kirkham and Bavel showed lower values due to land use previous 30 years and high water content values, and after two days of rain showed slow response of the improperly maintained drainage system.

The improper management of systems was directly related to privatization of drainage systems, high fragmentation of ownerships, no institutions or developed model that have integrated records or any responsibility for maintenance or protection of drainage systems. The full rehabilitation of drainage systems will require sufficient monitoring of different important parameters such as surface runoff, subsurface drain discharge, water level, sediments and some other less significant parameters, in order to regain a functionality and performance of controlled drainage.

Further research should be focused on maintenance of water table, outflow, levels of nitrogen and phosphorous, climate conditions in the area (floods and droughts), addition of fertilizers, pesticides or other chemical components to fully understand the long term effects of improperly maintained drainage systems, and to find a proper pattern-model for any future maintenance.

Comparative analysis of the results in countries with similar climate conditions and soil types showed some promising results in this respect. When the system is monitored and when the established patterns are followed, the performance effectiveness correlation can be drawn. With further maintenance of this type of soil and effective system, water management with controlled drainage can potentially lead to outstanding results.

8. Bibliography

Abbott, C., Lo Cascio, A., Gawad, S.A., Morris J, and Hess T. 2002. Guidelines for Controlled Drainage. HR Report OD147. HR Wallingford, U.K.

Äijö, H. 2012. Drainage in Finland. Field Drainage Association, Tartu, available online: http://lmb-melio.lv/files/file/seminar_201205_aijo.pdf, accessed in May 2020.

ASTM International. 2014. Importance of Particle Size Distribution Emphasized in Proposed ASTM Soil and Rock Standards, available online https://www.astm.org/cms/drupal-7.51/newsroom/importance-particle-size-distribution-emphasized-proposed-astm-soil-and-rock-standards accessed in May and June 2020.

Ayars, E., Christen, E.W., and Hornbuckle, J.W. 2006. Controlled drainage for improved water management in arid regions irrigated agriculture. Agricultural Water Management, 86, 128–139.

Ballantine, D., and Tanner, C. 2013. Controlled drainage systems to reduce contaminant losses and optimize productivity from New Zealand pastoral systems, Journal of Agricultural Research, 56(2), 171-185.

Báťková, K., Matula, S., and Miháliková, M. 2013. Multimedial Study Guide of Field Hydropedological Measurements (on-line). English version. Czech University of Life Sciences Prague, Prague, Czech Republic. No pagination, available at: http://hydropedologie.agrobiologie.cz. accessed in April 2020.

Bonaiti, G., and Borin, M. 2010. Efficiency of controlled drainage and sub-irrigation in reducing nitrogen losses from agricultural fields. Agricultural Water Management, 98(2), 343–352.

Brazdil, R., and Kirchner, K. 2007. Vybrané přírodní extrémy a jejich dopady na Moravě a ve Slezsku. Masaryk University, Czech Hydrometeorology Station.

Brozova, M., and Uurman, K. 2019. Agriculture in Czech Republic. Europea International, available online https://europea.org/agriculture-in-the-czech-republic/, accessed in May 2020.

Burt, R. 2011. Soil Survey Laboratory Information Manual. United States Department of Agriculture. Natural Resources Conservation Service, Soil Survey Laboratory.

Busman, L., and Sands, G. 2002. Agricultural Drainage. Issues and Answers, University of Minnesota Extension Service n. MI07740.

Carstensen, M.W., Børgesen, C.D., Ovesen, N.B., Poulsen, J.R., Hvid, S.K., and Kronvang, B. 2019. Controlled Drainage as a Targeted Mitigation Measure for Nitrogen and Phosphorus. Journal of Environmental Quality 48(3), 677-685.

Chandra, S., and De, S.K. 1976. A simple laboratory apparatus to measure relative erodibility of soils. Soil science, 125(2), 115-121.

Cui, J., Shao, G.,Yu, S., and Cheng, X. 2016. Influence of Controlled Drainage on the Groundwater Nitrogen and Phosphorus Concentration at Jointing-Booting Stage of Wheat. Journal of Chemistry.

Danhelka, J., Drbai, K., Štěpánková, P. 2009. Flash floods in Czech Republic – event of 2009 and method of flash flood risk evaluation. Thematic Workshop on Implementation of the Floods Directive 2007/60/EC, available online https://www.isprambiente.gov.it/files/acque/p1-paper-danhelka-etal.pdf accessed in April 2020.

De Wrachien, D. 2001. Irrigation And Drainage: Trends And Challenges For The 21 St Century. In Sustainable Use of Land and Water, Agroproject, Prague.
European Commission. 2017. Climate and Environmental challenges facing agriculture and rural areas, available online: https://ec.europa.eu/info/sites/info/files/food-farming-

fisheries/key_policies/documents/env_background_final_en.pdf accessed in March 2020

Evans, R.O., Skaggs, R.W., and Gilliam, J.W. 1995. Controlled versus conventional drainage effects on water quality. Journal Irrigation Drainage Engineering, 121(4), 271-276.

FAO, 2016. Climate change and food security: risk and responses, paper, available online: http://www.fao.org/3/a-i5188e.pdf, accessed in March 2020.

FAO, n.d. Food production and resource management, available online: http://www.fao.org/3/u7260e/u7260e04.htm, accessed in May 2020.

Fausey, N.R. 2005. Drainage management for humid regions. International Agricultural Engineering Journal, 14(4). 209-214.

Foged, H.L. and Hvid, S.K. 2012. Controlled drainage and other SCIEN drainage technologies. Agro Business Park., available online at: https://www.agrotechnologyatlas.eu/docs/Controlled_drainage_and_other_SCIEN_drainage_technologies_EN.pdf, accessed in April 2020.

Frankenberger, J., Kladivko, E., Sands, G., and Jaynes, D.B. 2004. Drainage Water Management for the Midwest, available online https://lib.dr.iastate.edu/cgi/viewcontent.cgi?article=1000&context=abe_eng_extensionpubs accessed in April 2020.

Golmohammadi, G., Prasher, S.O., Madani, A., Rudra, R. P., and Youssef, M.A. 2016. SWATDRAIN, a new model to simulate the hydrology of agricultural Lands, model development and evaluation. Biosystems Engineering, 141, 31-47.

Helmers, M., Pederson, C., Craft, K., and Schott, L. 2017. Impact of Drainage Water Management on Crop Yield, Drainage Volume, and Nitrate Loss. Iowa State University Research and Demonstration Farms Progress Reports, (10).

Hill, K., Hodgkinkson, R., Harris, D., and Newell, P. 2018. Field drainage guide Principles, installations and maintenance. AHDB, available online https://ahdb.org.uk/drainage, accessed in March 2020.

Husk, B. R., Anderson, B.C., Whalen, J.K., and Sanchez, J.S. 2017. Reducing nitrogen contamination from agricultural subsurface drainage with denitrification bioreactors and controlled drainage. Biosystems engineering. 153. 52-62.

Jacks G. 2019. Drainage in Sweden -the past and new developments. Acta Agriculturae Scandinavica Section B- Soil & Plant Science. 69(5). 405-410.

Jakeman, J.A., Barreteau, O., Hunt, R.J., Rinaudo, J.D., Ross, A., Arshad M., and Hamilton S. 2016. An overview of Concepts and Challenges in Integrated Groundwater Management - Concepts, Approaches and Challenges, (pp.3-20). Springer, Cham.

Jamieson, R.C., Gordon, R.J., Sharples, K.E., Stratton, G.W. and Madani, A. 2002. Movement and persistence of fecal bacteria inagricultural soils and subsurface drainage water: A review. Canadian Biosystems Engineering. 44(1). 1-9.

Jang, J., Anderson, E.L., Venterea, R.T., Sadowsky, M.J., Rosen, C.J., Feyereisen, G.W., and Ishii S. 2019. Denitrifying Bacteria Active in Woodchip Bioreactors at Low-Temperature Conditions. Frontiers in Microbiology, 635.

Jarvis, N., Koestel, J., Messing, I., and Moeys, J. 2013. Influence of soil, land use and climatic factors on the hydraulic conductivity of soil. Hydrology and Earth System Sciences Discussion. 10(8).

Jaynes, D.B., Kasper, T.C., Moorman, T.B., and Parkin, T.B. 2008. In situ bioreactors and deep drainpipe installation to reduce nitrate loss in artificially drained fields. Journal Environmental Quality. 37(2). 429-436.

Jonasz, M., and Fournier, G.R. 2007. Particle Size Distribution. Light Scattering by Particles in Water, Theoretical and Experimental Foundations Chapter 5.267-445

Karegoudar, A.V., Vishwanath, J., Anand, S.R., Rajkumar, R.H., Ambast, S.K., and Kaledhonkar, M.J., 2019. Feasibility of Controlled Drainage in Saline Vertisols of TBP Command Area of Karnataka, India, Irrigation and Drainage. 68. 969–978.

Kirkham, D., and van Bavel, C.H. 1948. Theory of seepage into auger holes, Proc. Soil Sci. Soc. Amer., 13, 75 – 82.

Kroger, R., Cooper, C.M., and Moore, M.T. 2008. A preliminary study of an alternative controlled drainage strategy in surface drainage ditches: Low-grade weirs, Agricultural Water Management. 95. 678-684.

Kulhavy, Z.1988. Regulation drainage Kolesa-Vapno, AGROPROJEKAT, VUMOP.

Kulhavy, Z., and Pelišek, I. 2017. Conditions for the sustainability of agriculture drainage structures. Available on: http://www.hydromeliorace.cz/omega2/data_zk/vh_06-2017.pdf, accessed in April 2020.

Lavairea, T., Gentrya, L.E., Davida, M. B., and Cooke, R. A. 2017. Fate of water and nitrate using drainage water management on tile systems in east-central Illinois. Agricultural Water Management. 191. 218-228

Libohova, Z.,Schoeneberger, P., Bowling, C.L., Owens, P.R., Wysocki.,Wills S.,Williams C.O., and Seybold C. 2018. Soil Systems for Upscaling Saturated

Hydraulic Conductivity for Hydrological Modeling in the Critical Zone. Vadose Zone Journal, 17(1). 1-20.

Lu, B., Shao, G., Yu, S., Wu, S., and Xie, X. 2016. The Effects of Controlled Drainage on N Concentration and Loss in Paddy Field, Journal of Chemistry.

Ministry of Agriculture of the Czech Republic. 2018. Report on Water Management in the Czech Republic in 2018, http://eagri.cz/public/web/en/mze/publications/publications-water/report-on-water-management-in-the-czech-5.html, accessed in April 2020.

Ministry of Agriculture and Environment. 2015, Report on Water Management in the Czech Republic in 2015, http://eagri.cz/public/web/en/mze/publications/publications-water/report-on-water-management-in-the-czech-2.html, accessed in April 2020.

Mohsenipour, M. and Shahid, S. 2016. Estimation Of Saturated Hydraulic Conductivity: A Review. Malasia: Academia Edu. Available online http://bit. ly/2WShxfW, accessed in April 2020.

Molen V.D, W.H., Beltran, J.M., and Ochs, W.J. 2007. Guidelines and computer programs for the planning and design of land drainage systems, Food and Agricultural Organization of the United Nations FAO, Rome, available online http://www.fao.org/docrep/010/a0975e/a0975e00.htm, accessed in April 2020.

Owens, S., and Cowell, R. 2011. Land and limits: interpreting sustainability in the planning process. Routledge.

Pandey, P.K., Kass, P.H., Soupir, M.L., Biwas, S., and Singh, V.P. 2014. Contamination of water resources by pathogenic bacteria. Amb Express. 4(1), 51.

Pérez-Lucas, G.,Vela, N., El Aatik, A., and Navarro S. 2018. Environmental Risk of Groundwater Pollution by Pesticide Leaching through the Soil Profile. In Pesticides use and misuse and their impact in their environment. IntechOpen.

Poole, C. A., Burchell, M., and Youssef, M. A. 2018. Controlled Drainage – An Important Practice to Protect Water Quality That Can Enhance Crop Yields. NC State Extension Publications.

Povilaitis, A., Rudzianskaitė, A., Misevičienė, S., Gasiūnas, V., Miseckaitė O.,and Živatkauskienė I. 2018. Efficiency of Drainage Practices for Improving Water Quality in Lithuania, Transactions of the Asabe. 61(1). 179-196.

Rekacewicz, P. 2006. Increased global water stress. Available online: https://www.grida.no/resources/5625 accessed in April 2020.

Ritter, J.P. and Eng, P. 2012. Soil erosion – Causes and Effects. OMFRA Factsheet 10. 12-53.

Ritzema, H. and Styut, L.C. 2015. Land drainage strategies to cope with climate change in the Netherlands, Acta Agriculturae Scandinavica, Section B. Soil and Plant Science. 65(1). 80–92

Skaggs, R.W., Youssef, M.A., Gilliam, J.W., and Evans, R.O. 2010. Effect of controlled drainage on water and nitrogen balances in drained lands. Transactions of the ASABE .53(6). 1843– 1850.

Skaggs, R.W., Fausey, N.R., and Evans, R.O. 2012. Drainage water management. Journal Soil Water Conservation, 67(6). 167– 172.

Sojka, M., Kozłowski, M., Stasik, R., Napierała, M., Kesicka, B., Wrózynski, R., Jaskuła, J., Liberacki, D., and Bykowski, J. 2019. Sustainable Water Management in

Agriculture-The Impact of Drainage Water Management on Groundwater Table Dynamics and Subsurface Outflow. Sustainability. 11(15). 4201.

Schyns, J.F., Hoekstra, A.Y., Booij, M. J., Hogeboom, R. J., and Mekonnen, M.M. 2019. Limits to the world's green water resources for food, feed, fiber, timber, and bioenergy. Proceedings of the National Academy of Sciences. 116(11). 4893-4898.

Singh, O. P. 1996. Integration of irrigation and drainage management in a monsoonic climate. ICLD, 25, 139.

Stuyt, L. C. P. M., Dierickx, W., and Beltrán, J. M. 2005. Materials for subsurface land drainage systems (No. 60). Food & Agriculture Organization.

Tan, C.S., Zhang, T. Q., Drury, C. F. and Reynolds, D. 2007. Water Quality and Crop Production Improvement Using a Wetland-Reservoir and Draining/Subsurface Irrigation System. Canadian Water Resources Journal, 32(2), 129–136.

Tlapáková, L., Žaloudík, J., Kulhavý, Z., and Pelíšek, I. 2015. Use of remote sensing for identification and description of subsurface drainage systém condition. Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis, 63(5), 1587–1599.

Tlapáková, L., Žaloudík, J., & Kolejka J. 2017. Thematic survey of subsurface drainage systems in the Czech Republic, Journal of Maps, 13(2), 55-65.

UN 2019 World Population Prospects 2019, available online https://population.un.org/wpp/ accessed in May 2020.

UNDP 2006 Human Development Report, Beyond scarcity: Power, poverty and the global water crisis. United Nations Development Program UNDP.

USDA, N 2001. National Engineering Handbook, Part 650, Engineering Field Handbook, Chapter 14. Water Management (Drainage).

Valero, C.S., Madramootoo, C.A., and Stampfli, N. 2007. Water table management impacts on phosphorus loads in tile drainage. Agricultural Water Management, 89, 71–80.

Valipour, M. 2014. Drainage, waterlogging, and salinity, Archives of Agronomy and Soil Science, 60(12), 1625-1640.

Valipour, M., Krasilnikof, J., Yannopoulos, S., Kumar, R., Deng, J., Roccaro, P., Mays, L., Grismer, M.E., and Angelakis, A.N, 2020. The Evolution of Agricultural Drainage from the Earliest Times to the Present, Sustainability, 12 (1), 416.

Vanham, D., Bouraoui, F., Leip, A., Grizzetti, B., and Bidoglio, G. 2015. Lost water and nitrogen resources due to EU consumer food waste. Environmental Research Letters. 10(8), 084008.

Vlotman, W. F., and Jansen, H.C. 2003. Controlled drainage for integrated water management. 9th International Drainage Workshop, Utrecht, the Netherlands.

Vlotman, W.F. 2017. Beyond Modern Land Drainage Irrigation and Drainage. In 13th International Drainage Workshop of ICID.

Wahba, M.A.S., El-Ganainy, M., Abdel-Dayem, M.S , Gobran, A., and Kandil, H.2001. Controlled Drainage Effect on Water Quality under Semi-Arid Conditions in The Western Delta of Egypt. Irrigation and Drainage, 50, 295–308.

Wesstrom, I., Messing, I., Linner, H., Lindstrom J. 2002. Controlled drainage-effects on drain outflow and water quality. Agricultural water management, 47(2), 85-100.

Xiao, M., Hu, X., and Chu, L. 2015. Experimental study on water-saving and emission-reduction effects of controlled drainage technology, Water Science and Engineering, 8(2), 114-120.

Youssef , M. A., Abdelbaki, A. M., Negm, L. M., Skaggs, R. W., Thorp, K.R., and Jaynes, D.B. 2018. DRAINMOD-simulated performance of controlled drainage across the U.S. Midwest. Agricultural Water Management, 197, 54–66.

Zimmer, D. and Madramootoo C. 2007. Water table management, Food and Agriculture Organization, available online http://www.fao.org/3/w7224e/w7224e07 accessed in May 2020.