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Evaluating the Impact of Digestate on Soil-Water Dynamics and Hydraulic Properties in Agricultural Soils: A Case Study from Emilia-Romagna

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Contents

1. INTRODUCTION

The venture is set inside the system of yearly trim generation in nitrate-vulnerable ranges and inside zones, which confront critical challenges due to routine agrarian hones and the impacts of climate alter. The arrange points to address these issues through inventive and maintainable hones. Its essential targets are the definition of the part of soil natural matter in diminishing nitrate contamination and the diminishment of herbicide utilize in crops debilitated by climate alter, such as corn, through traditionalist agronomic hones. These hones incorporate the utilize of cover crops and digestate, as proposed by the unused National Vital Arrange for the CAP (Common Agrarian Arrangement) 2023-27.
It is presently well built up that preservation farming mitigates climate alter by diminishing inputs and expanding soil carbon stocks, which moreover contributes to progressing soil structure. This venture will utilize areas where preservation farming hones have been compared with conventional hones since 2017, permitting for an assessment over a seven-year period. The utilize of cover crops and digestate will permit for the appraisal of their added substance impacts on supplement accessibility and soil biodiversity.

The DICO SOS venture has the taking after particular objectives:

- To compare soil carbon substance between preservation and conventional agriculture
- To develop the understanding of the impacts of more prominent natural matter accessibility on nitrate evacuation for contamination prevention
- To create a convention for the utilize of cover crops in trim revolutions to diminish herbicide use
- To decrease the utilize of manufactured fertilizers through the application of natural corrections and cover crops
- To carry out a microbiological characterization of soils beneath distinctive agronomic practices

Coherence of the arrange with the particular topical needs of Center Region 16.1.1

The goals of this Arrange are reliable with the objectives of the particular mediation zones and advancements of Center Zone 4B. The Arrange of the GO (Operational Bunch) completely addresses all three topical needs sketched out in the call for proposals:

Reducing the discharge of poisons and progressing water and soil quality

The application of traditionalist agronomic hones, such as no-till and least culturing, combined with the utilize of cover crops and digestate, advances an increment in soil natural matter and the coming about forms of denitrification. This diminishes filtering wonders and increments water maintenance, whereas the cleaning impact of cover crops makes a difference to diminish the utilize of herbicides. A particular objective is to protect both soil and water resources.

Controlling bugs with low-impact methods

The combined utilize of cover crops and digestate permits for a diminishment in chemical inputs, such as herbicides and manufactured fertilizers. A particular objective is to control the nearness of weeds through cover crops, decreasing the require for herbicides. At the same time, the utilize of digestate not as it were decreases the require for engineered fertilizers but too upgrades soil biodiversity and advances a more created root system.

Adapting rural editing frameworks to climate change

The collaboration between low-input rural operations, cover crops, and digestate permits ranches to gotten to be more flexible in confronting climate alter in a down to earth and financially maintainable way. The increment in soil natural matter and biodiversity empowers a more strong root framework able of making the best utilize of accessible assets without exhausting them. Also, the utilize of cover crops expands trim turns and keeps the soil secured for longer periods. The particular objective is to cultivate the adjustment of editing frameworks by expanding natural matter and amplifying turns, making them less defenseless to extraordinary climate occasions such as strongly precipitation or delayed drought.

Detailing the project's targets and their broader impact

The to begin with objective of comparing carbon substance between preservation and conventional rural frameworks is principal, as soil carbon is a key pointer of soil wellbeing and richness. Carbon sequestration in soil contributes altogether to moderating climate alter by acting as a carbon sink. Through long-term perception of areas that have executed preservation hones for seven a long time, the extend points to give vigorous information to approve these strategies as a implies of lessening carbon outflows and progressing soil resilience.

Furthermore, by investigating the impacts of expanded natural matter on nitrate expulsion, the venture handles the pressing issue of nitrate contamination, especially in helpless regions. Abundance nitrates from agrarian runoff contribute to water defilement, influencing both human wellbeing and oceanic environments. By analyzing how natural matter upgrades microbial movement and underpins characteristic denitrification forms, the venture points to create procedures for diminishing the natural effect of farming whereas keeping up tall productivity.

The advancement of a cover edit convention for edit revolution is another basic viewpoint. Cover crops, such as vegetables and grasses, give a few biological system administrations, counting weed concealment, soil disintegration control, and enhancement of soil structure and richness. By lessening the dependence on herbicides, cover crops contribute to more maintainable agrarian hones that are less destructive to the environment and human health.

Reducing engineered fertilizer utilize through the application of natural alterations, such as digestate, adjusts with worldwide endeavors to move toward more natural and circular rural frameworks. Digestate, a byproduct of anaerobic assimilation, is wealthy in supplements and can serve as an successful elective to chemical fertilizers. Its utilize not as it were reuses squander but moreover upgrades soil ripeness and underpins the long-term maintainability of rural systems.

Lastly, the microbiological characterization of soils beneath distinctive agronomic hones points to reveal the complex intuitive between soil living beings and cultivating strategies. Soil biodiversity is a significant component of biological system wellbeing, affecting supplement cycling, plant development, and strength to infections and bugs. By understanding how preservation hones influence soil microbial communities, the venture looks for to create rules for optimizing soil wellbeing and productivity.

Broader suggestions for agrarian arrangement and sustainability

The venture is profoundly important to current rural approaches at both the national and European levels, especially inside the system of the CAP 2023-27. The accentuation on preservation hones, decreased chemical inputs, and climate adjustment reflects the broader objectives of maintainable escalated, where efficiency is kept up or expanded whereas minimizing natural impacts.

By contributing to the improvement of best hones for cover crops and digestate utilize, the extend bolsters the move to agroecological strategies that prioritize environmental forms and asset productivity. The discoveries seem illuminate future approaches pointed at advancing soil wellbeing, lessening chemical reliance, and improving the flexibility of agrarian frameworks to climate change.

Moreover, the project's center on nitrate-vulnerable regions and inside districts addresses particular topographical challenges where rural hones have a unbalanced effect on nearby environments. These ranges are regularly characterized by delicate situations that are especially touchy to contamination and debasement, making feasible hones indeed more critical.

In conclusion, the DICO SOS extend is a forward-thinking activity that looks to accommodate rural efficiency with natural maintainability. By advancing preservation hones, decreasing chemical inputs, and improving soil wellbeing, the venture points to make a demonstrate for flexible cultivating frameworks able of withstanding the challenges of climate alter. Its victory seems to serve as an outline for other locales confronting comparable challenges, advertising viable arrangements for building a more economical rural future.

1.1 State of Art

The state of the art is a critical section of any thesis, providing a comprehensive review of existing research, theories, methodologies, and technological advances related to the topic under investigation. In the context of studying soil salinity, moisture dynamics, and temperature variations, particularly concerning the use of digestate and control treatments in agricultural practices, the state of the art should delve into several intertwined domains: soil science, environmental monitoring, agricultural waste management, and hydrology.

Soil plays a pivotal role in sustaining agriculture, acting as a medium for plant growth, a regulator of water, and a habitat for numerous microorganisms. The structure, composition, and health of soil are central to determining its suitability for different types of crops. Over the last several decades, the scientific community has increasingly focused on understanding how various human activities, such as fertilization and waste management, impact soil properties. Soil health is not only influenced by its chemical makeup but also by its physical and biological properties.

A significant body of research has highlighted the importance of maintaining a balanced nutrient profile in soils. Fertilizers—whether synthetic, organic, or bio-based—are essential for replenishing soil nutrients that crops absorb. However, the excessive use of chemical fertilizers can lead to soil degradation, nutrient imbalances, and environmental pollution, including eutrophication of water bodies due to nutrient runoff. This has led to a growing interest in alternative soil amendments, such as organic waste products like digestate.

One of the most critical factors affecting soil fertility is salinity. High salinity levels can severely impair plant growth, reduce agricultural yields, and damage soil structure by influencing water absorption mechanisms in plants. The global concern regarding salinity has been escalating as regions experiencing water scarcity increasingly rely on saline or brackish water for irrigation. As soils become more saline, they pose a threat to long-term agricultural sustainability. Researchers have dedicated significant efforts to understanding how different treatments—such as digestate or traditional fertilizers—impact the salinity levels of soils.

Environmental monitoring technologies have advanced rapidly, providing researchers with a robust set of tools to observe and analyze soil conditions in real time. In particular, monitoring salinity, moisture, and temperature at various soil depths has become central to evaluating the effects of different treatments on soil dynamics.

Salinity monitoring in soils is typically conducted through various methods, including electromagnetic sensors, conductivity probes, and remote sensing techniques. The depth at which salinity is measured is also of importance, as the salinity profile can differ significantly from the surface to deeper layers of soil. As salinity moves downward due to rainfall or irrigation, deeper layers can accumulate salts that later resurface during periods of evaporation or drought. This creates a cyclical challenge for maintaining soil health in the long term. In agricultural systems, salinity is also affected by the type of soil amendment used, with organic amendments sometimes buffering the soil against salinity increases and at other times contributing to salt accumulation, as seen in the application of digestates.

Soil moisture is another critical parameter in assessing soil health. Moisture availability affects plant water uptake, nutrient transport, and the overall biological activity within the soil. In terms of monitoring, advanced sensors now allow continuous real-time tracking of moisture at various depths. This is particularly useful when studying how different treatments, like the application of digestate, affect the retention and distribution of water within the soil profile. Previous studies have shown that organic treatments may increase soil moisture retention due to improvements in soil structure and increased organic matter content, which acts as a sponge for water. However, results can vary depending on soil type, climate, and the quality of the organic amendment applied.

Soil temperature influences numerous processes, including nutrient cycling, microbial activity, and water evaporation. Thus, monitoring soil temperature is critical when examining the effects of different soil treatments. Temperature changes can also influence salinity and moisture levels indirectly, as increased temperatures can lead to faster evaporation rates, concentrating salts at the surface and reducing the overall water content in the soil. Environmental monitoring of temperature at various depths provides insight into how different treatments may buffer or exacerbate these processes.

Digestate, the byproduct of anaerobic digestion, has emerged as a promising alternative to traditional fertilizers in modern sustainable agricultural practices. It is produced from organic waste, including food residues, livestock manure, and crop by-products. During anaerobic digestion, organic matter is broken down by microorganisms in the absence of oxygen, resulting in the production of biogas (primarily methane) and digestate, a nutrient-rich slurry.

Digestate contains valuable nutrients such as nitrogen, phosphorus, and potassium, which are essential for plant growth. Additionally, it contributes organic matter to the soil, improving soil structure, water retention, and microbial activity. However, digestate also carries salts, and depending on its composition, it can increase the salinity levels in soils, as observed in some studies.

Several research initiatives have focused on characterizing the nutrient profile of digestate, as well as understanding how its application impacts different types of soil. One challenge that has emerged is the variability in the composition of digestate, which depends on the input materials used in the anaerobic digestion process. While some digestates may enhance soil fertility and structure, others may lead to the accumulation of salts or heavy metals, particularly when produced from non-agricultural organic waste.

Understanding the movement of water within the soil is key to predicting how treatments like digestate or traditional fertilizers affect soil health. Hydrological studies within the agricultural domain often focus on the infiltration rate, water holding capacity, and the movement of solutes, such as salts or nutrients, within the soil profile. In dryland agriculture or regions dependent on irrigation, these dynamics become even more critical, as water scarcity can exacerbate the negative impacts of high salinity or poor soil structure.

Infiltration refers to the movement of water from the soil surface into the soil profile, while water retention refers to the soil's ability to hold onto water. Various factors influence both processes, including soil texture, structure, and organic matter content. Treatments such as digestate may alter these processes by changing soil porosity and increasing organic matter. This can either improve or reduce water infiltration and retention, depending on the specific characteristics of the digestate and the soil it is applied to. For instance, digestate applications in sandy soils may improve water retention, while in heavy clay soils, it may lead to waterlogging.

The movement of solutes, particularly salts and nutrients, within the soil profile is a complex process influenced by water flow, soil texture, and treatment application. As water percolates through the soil, it can carry dissolved salts downward, leading to salt accumulation in deeper soil layers. This phenomenon is often referred to as "leaching." However, during periods of evaporation or reduced rainfall, these salts can move back upward through capillary action, leading to surface salt accumulation. The application of digestate can influence this process by altering the soil's chemical and physical properties, either exacerbating or mitigating the risks associated with salinity.

The environmental implications of soil salinity and moisture management are significant, particularly in the context of climate change and global food security. As water scarcity becomes more pronounced in various parts of the world, the ability to manage salinity levels and water retention in soils will be critical to maintaining agricultural productivity. Sustainable soil management practices, including the use of digestates and other organic amendments, offer potential solutions to these challenges, but they must be carefully studied and applied to avoid unintended consequences.

Research into the long-term impacts of digestate application is still emerging, but preliminary findings suggest both benefits and challenges. On the positive side, digestate can enhance soil fertility, increase organic matter content, and improve soil structure. However, there are concerns about the accumulation of salts and other contaminants over time, particularly when digestate is applied repeatedly or in large quantities. Understanding the long-term interactions between digestate, soil properties, and environmental factors is critical to developing guidelines for its sustainable use.

While significant progress has been made in understanding the effects of soil treatments on salinity, moisture, and temperature, several gaps in the research remain. One key area of uncertainty is the variability in digestate composition and its effects on different soil types. There is also a need for long-term studies to assess the cumulative impacts of digestate applications on soil health, particularly concerning salinity and nutrient accumulation. Moreover, the interactions between digestate and other soil amendments, such as biochar or compost, are still poorly understood.

In conclusion, the state of the art in soil management, particularly concerning the use of digestate, highlights both the potential benefits and risks associated with this practice. While digestate offers a sustainable alternative to chemical fertilizers, its impact on salinity, moisture retention, and soil structure requires further investigation to ensure its safe and effective use in agriculture. The current body of research provides a strong foundation for future studies, which should focus on long-term monitoring, regional variability, and the development of best practices for digestate application.

1. EXPERIMENTAL FIELDS

The study area for this project and the subject of this thesis comprises the distinct agricultural fields situated in the Emilia-Romagna region, within the province of Ferrara.
The field is located in the central-eastern area of Ferrara province, near Gualdo (GPS coordinates: 44°47'37.6278"N, 11°42'22.5148"E), on loamy clay soils. Similar to the first, this land is flat but lies above sea level, with elevations ranging from 2.40 to 3 meters. In terms of farm size and crop type, it represents medium-to-large farms in the region, also dedicated to the cultivation of cereals and protein crops. Both sites are crucial for understanding the agricultural practices in Ferrara and their impact on soil and crop management.

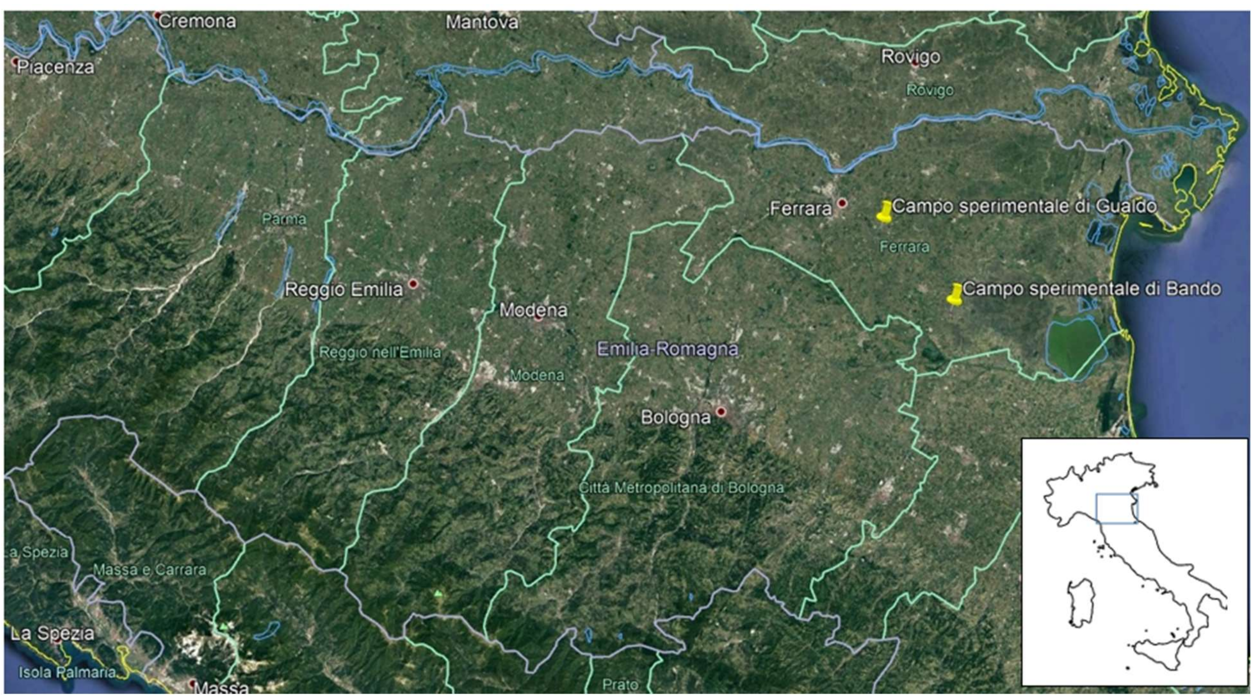


Figure 1: Image taken from Google Earth with the location of the two experimental fields highlighted.

2. HYDROGEOLOGICAL SETTING

The aquifer system in the Emilia Romagna region is organized into three major aquifer groups (referred to as A, B, and C from top to bottom), which are separated by significant aquitards. This thesis specifically focuses on the phreatic aquifer A0. In some cases, particularly in areas where ancient riverbeds of the Po are present, aquifer A0 may merge with aquifer A1. Therefore, the scope of this study includes a brief description of these two interconnected aquifers, A0 and A1, as they are the primary focus of the research carried out.

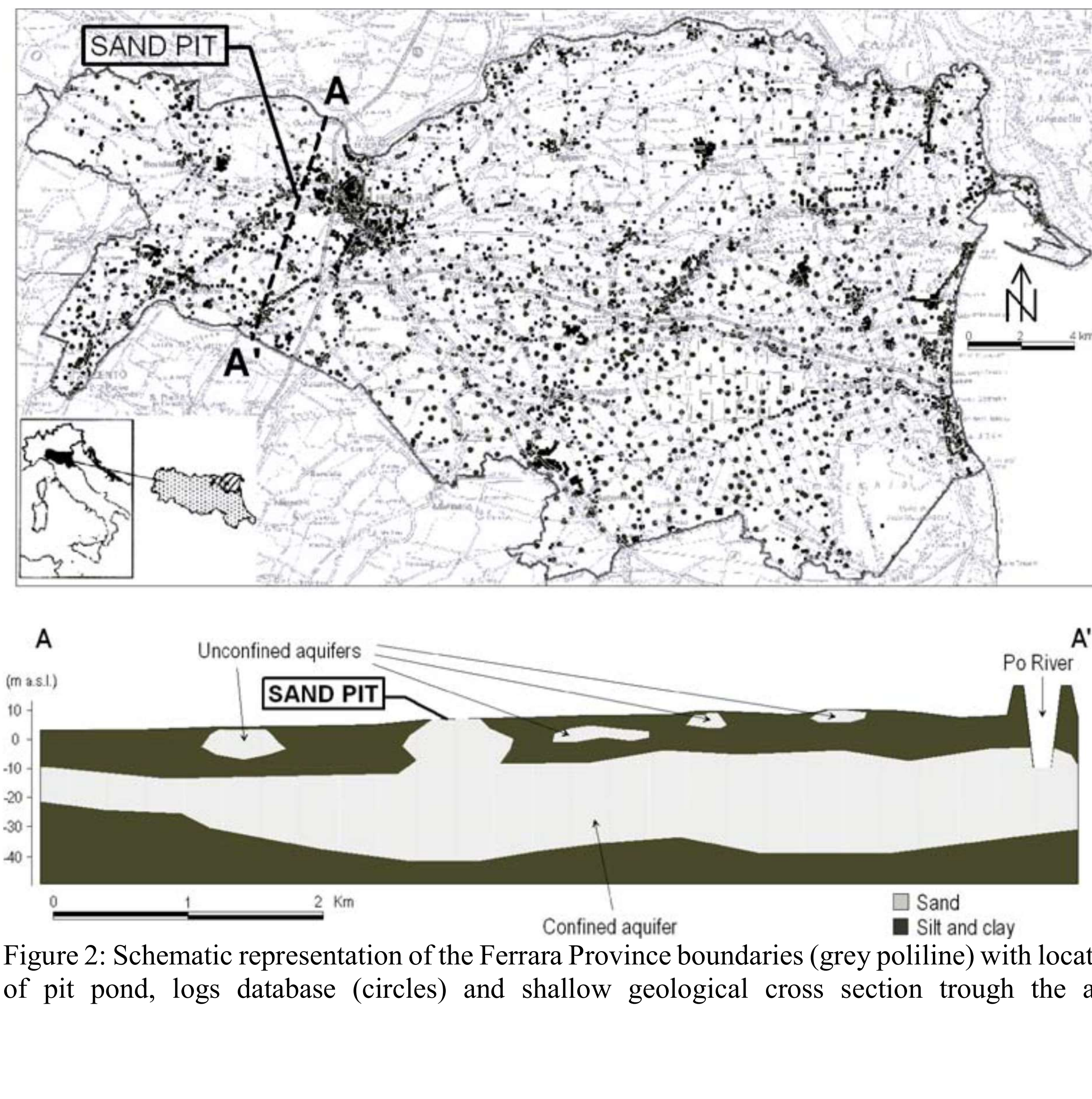


Figure 2: Schematic representation of the Ferrara Province boundaries (grey poliline) with location of pit pond, logs database (circles) and shallow geological cross section trough the area

(Mastrocicco, Colombani , & Palpacelli , Fertilizers mobilitation in alluvial aquifer: laboratory experiments., 2009).

The A0 aquifer complex

The A0 complex represents the phreatic aquifer, which is the main focus of the groundwater analysis in this thesis. This aquifer has a unique stratigraphic structure that distinguishes it from other nearby aquifer systems. In the inland areas, the deposits consist of porous, permeable sediments from meandering plains, primarily linked to channels of Po Valley origin and proximal embankments formed from Apennine sediments. In contrast, coastal regions are characterized by more permeable deposits, including those associated with ancient shoreline ridges and wind-formed dunes.

The A0 aquifer shows varying horizon thicknesses, with more substantial deposits found in the coastal regions and thinner layers along the paleo-riverbeds in the central-northern parts, nearer to Ferrara. The thicker deposits in coastal areas are typically composed of shoreline or dune sands, averaging 5 to 10 meters in thickness. In contrast, channel-fill deposits, both continental and coastal, are primarily sandy and are encased in deltaic or marshy clays and silts that act as aquitards for the A0 system. These deposits typically range from 3 to 6 meters thick (Underground Water Resources of the Province of Ferrara, 2007). Occasionally, sand deposits of Po Valley origin can blend with the underlying A1 aquifer system, reaching thicknesses of up to 40 meters.

Despite the presence of a fair amount of sandy deposits, including some coarser materials, groundwater circulation within this aquifer complex is generally limited. Moreover, interactions with surface water are primarily restricted to the shallower aquifers, particularly A0 and A1 (Underground Water Resources of the Province of Ferrara, 2007; Mastrocicco, Colombani, Salemi, Vincenzi, & Castaldelli, 2012).

The image (fig 3) presented below illustrates a soil core sample contained within a transparent cylindrical apparatus. This sample was extracted during fieldwork aimed at analyzing the stratigraphy and properties of the soil in situ. The visible stratification of the soil core reveals layers with varying colors and textures, which suggest differences in soil composition, organic matter, and moisture content at different depths. Such stratification is essential for understanding soil dynamics, nutrient distribution, and the potential for water retention and infiltration.

The field site appears to be an open agricultural area, characterized by bare soil, indicative of either recently cultivated or fallow land. The presence of fieldwork tools, such as shovels, and a nearby vehicle suggest that the image was taken as part of a broader field study focused on soil sampling and analysis.

Figure 3. Samples taken from the agriculture field

This soil core is particularly valuable for examining various physical and chemical soil properties, such as compaction, porosity, and permeability. It also serves as a key dataset for evaluating the impacts of agricultural practices on soil health and fertility, particularly in relation to carbon sequestration and nutrient cycling, which are critical components of sustainable land management. Such analyses are central to the broader objectives of this research, providing insight into soil behavior under different agricultural or environmental conditions.

3.1 Experimental field of Gualdo

The experimental field located in Gualdo is classified under the soil type known as "Baura Franco clayey silty." These soils are characterized by their significant depth and moderate alkalinity, making them suitable for various agricultural activities. The upper layers of the soil exhibit a silty clay loam texture, which is moderately or highly calcareous, providing essential minerals like calcium for plant growth. In contrast, the lower layers have a silty loam or silty clay texture and are highly calcareous.

The underlying substrate is composed of alluvial deposits, with a medium to moderately fine texture, typical of floodplain soils. This stratification provides favorable conditions for water retention and nutrient availability, contributing to the overall fertility of the soil. The specific properties of Baura Franco clayey silty soils make them ideal for supporting crop production in the Gualdo region, especially for cereal and protein crops, which require well-drained yet moisture-retentive soils with adequate nutrient availability.

In agricultural terms, the combination of the calcareous nature of both the upper and lower horizons, along with the fine texture, supports strong root development and enhances soil aeration, making this type of soil particularly resilient to seasonal variations. The fertility of this soil type also aids in the sustainability of long-term crop rotation, an essential factor in modern agronomy practices focused on reducing the use of synthetic inputs while maintaining high productivity. This makes Gualdo's soil an excellent resource for experimental agricultural research and practices aimed at evaluating sustainable farming methods.

Figure 4: Soil stratigraphy of the experimental field of Gualdo.

3. MATERIALS AND METHODS

The research activities for this thesis were conducted both in the field and in the laboratory. In the field, chemical-physical parameters were monitored, and soil and groundwater samples were collected for analysis. The laboratory work involved preparing these samples and analyzing them using a spectrophotometer.

To track groundwater levels and quality, piezometers (2.5 cm in internal diameter) were installed at random within each treatment area on both farms. At the Gualdo experimental site, piezometers were installed at various depths for precise monitoring:

- Area A: five piezometers at depths of -2 m, -2.5 m, -3 m, -3.5 m, and -4 m from ground level.
- Area C: three piezometers at depths of -2 m, -3 m, and -4 m.
- Area M: three piezometers at depths of -2 m, -3 m, and -4 m.
- Area S: five piezometers at depths of -2 m, -2.5 m, -3 m, -3.5 m, and -4 m.

Additionally, in one of the treatments at each site, a Watermark Probe was installed to measure soil moisture and water potential. A nearby thermocouple was also placed to monitor soil temperature, which allowed for the adjustment and compensation of moisture measurements based on temperature variations. These instruments provided a detailed understanding of soil conditions, helping assess water retention, temperature effects, and potential impacts on agricultural productivity.

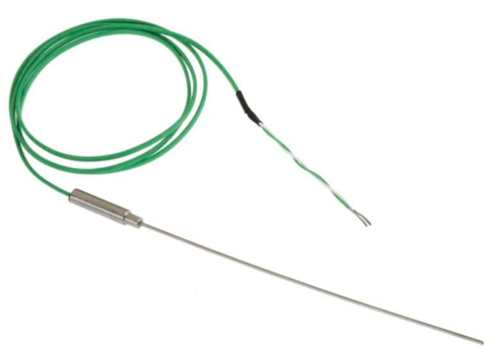


Figure 5: Thermocouple installed in the field to correct the readings.

Figure 6. Columns replicas with and without digestate.

The image (Fig. 6) shows a set of columns filled with soil material synthetic urea and digestate, used as part of an experimental setup to analyze how distilled water flows through the columns under varying conditions. Each column is equipped with sensors that measure critical parameters such as temperature, hydraulic conductivity, and moisture or humidity levels. These sensors provide real-time data that help researchers understand how water movement occurs within the soil structure when treated with digestate. This setup mimics natural processes but in a controlled laboratory environment, enabling precise observations of water infiltration, retention, and drainage patterns, which are essential for understanding soil-water interactions.

The columns differ in terms of their saturation levels. While all columns contain the same material, the difference in saturation allows the experiment to replicate a range of soil moisture conditions that could occur in the field. For example, some columns may simulate waterlogged conditions, while others replicate drier environments. This variability helps to assess the behavior of water under different circumstances, such as those found in various agricultural practices or natural events like rainfall and droughts.

The goal of the experiment is to observe the movement of water within these columns under the influence of digestate, which is used as a soil amendment in agriculture. Digestate, being rich in organic matter and nutrients, affects the hydraulic properties of the soil, potentially enhancing its water-holding capacity and nutrient retention. By measuring the flow of distilled water, the researchers can determine how effectively the soil retains moisture, how quickly water drains, and how the hydraulic conductivity changes over time. The use of digestate also introduces organic compounds into the soil, which could have an impact on the microbial activity and overall soil health.

The temperature sensors embedded in the columns help monitor any changes in thermal dynamics as the water flows through the soil-digestate mixture. Since soil temperature can influence water movement, microbial activity, and nutrient availability, tracking this parameter is crucial for understanding the overall effect of digestate on soil function. The hydraulic conductivity measurements, meanwhile, provide insights into how easily water moves through the soil profile under various moisture conditions, revealing any changes in the soil's permeability due to the addition of digestate.

Additionally, moisture or humidity sensors are used to determine the soil’s ability to retain water over time, which is critical for evaluating the effectiveness of digestate in improving soil structure and its potential for agricultural sustainability. These sensors track the water content at various depths in the columns, providing a detailed picture of how water is distributed within the soil.

The experiment, therefore, offers valuable information on how soil treated with digestate responds to water movement under different saturation levels. The findings could have significant implications for agricultural practices, particularly in areas vulnerable to drought or excessive rainfall. By improving soil's ability to manage water through amendments like digestate, farmers may be able to create more resilient cropping systems that can withstand the effects of climate change, such as increased water stress or nutrient leaching. Overall, this experimental setup is designed to shed light on the critical interactions between soil, water, and organic amendments, contributing to a more sustainable and efficient approach to land management.

Figure 7: emplaced drill&drop Sentek probes to monitor the soil water and solutes movements.

Figure 8: Experimental synthetic rainfall simulator and fraction collectors.

Furthermore, as shown in figures 7 & 8, the column digestates were simulated to have distilled rainwater falling from the top, creating a controlled environment to analyze the filtration and absorption capabilities of the materials within the columns. This setup allowed for precise measurements of the concentrations of nitrate and other potentially harmful elements as they percolated through the substrate, ultimately reaching the bottom levels of the column. By regularly monitoring these outflow levels, researchers aimed to assess the effectiveness of the digestate in mitigating contaminants, thereby gaining insights into its potential applications for environmental remediation. The study focused not only on nitrate but also on various other pollutants, enabling a comprehensive evaluation of the digestate's role in maintaining water quality and preventing pollution in agricultural and urban runoff scenarios. Furthermore, the findings could contribute valuable data to enhance sustainable waste management practices and support the development of more effective strategies for water treatment and soil health improvement.

4.1 Manual: Drill and drop method

This manual supports the Sentek Bluetooth Drill & Drop probe. The probe incorporates a Bluetooth Low Energy device that communicates using a Sentek proprietary GATT Profile that can communicate with a Sentek application in a mobile device.

The probe comes in four sensor configurations of 3, 6, 9 or 12 sensors (30, 60, 90 or 120cm), all moisture sensors or all TriSCAN sensors, together with a temperature sensor on each sensor.

The probe electronics are encapsulated in the probe rod which is integrated with a battery and a wireless Bluetooth antenna in the probe head.

Figure 9. Bluetooth Probe head incorporating battery compartment, antenna and serial number

This probe has similar functionality to other Sentek Drill & Drop Probes such as SDI-12 Series III or Sentek RS232/485 Series II probes incorporating a Sentek EnviroSCAN interface box.

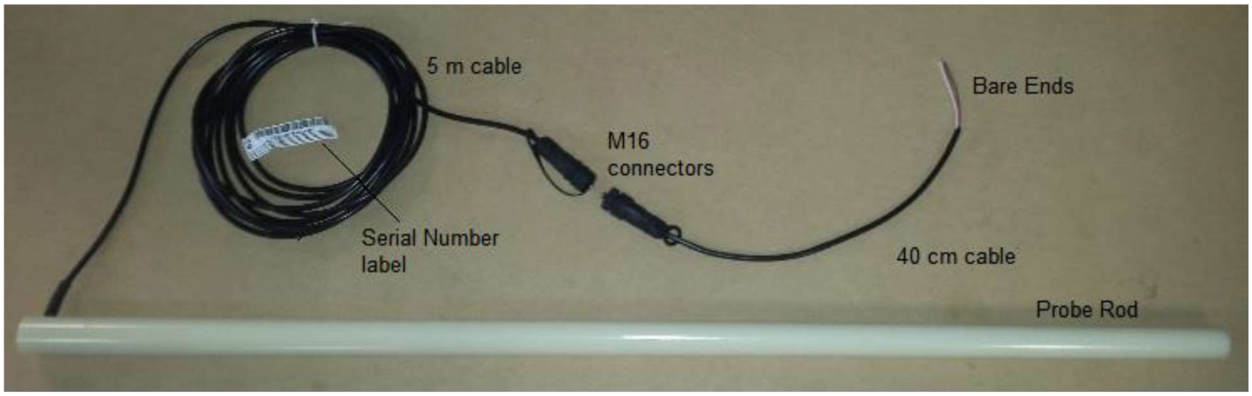


Figure 10. SDI12 Drill & Drop Series III

Probe Characteristics

The sensors are encapsulated inside the probe rod:

- 3, 6, 9 or 12 moisture sensors or
- 3, 6, 9 or 12 moisture and salinity sensors
- Every sensor has an associated temperature sensor
- Sensors are spaced at 10 cm intervals, with the first sensor and its temperature sensor centred at 5 cm below the base of the top cap. Probe length 30 cm (12 inches), 60 cm (24 inches), 90cm (32 inches) or 120 cm (48 inches)
- The probe is preconfigured with all sensors Air/Water normalised and calibration coefficients pre-set

Cables

- Probe cables are not required because all communications is via Bluetooth wireless communication.
- A mobile device charging/USB cable is needed

Installation and Setup of the Drill and Drop Probe

1. Introduction

The **Drill and Drop method** is a widely used approach for installing probes in environmental monitoring and soil research. This method allows researchers to measure key soil parameters, such as moisture content, temperature, and salinity, over time without disturbing the soil structure postinstallation. The data collected helps in understanding water movement, nutrient transport, and overall soil health, making it essential for studies related to agriculture, hydrology, and environmental science.

2. Equipment and Materials

- **Drill and Drop Probe**: Multi-sensor probe for measuring soil properties.
- **Soil Auger/Drill**: For creating a borehole to the appropriate depth.
- **Data Logger**: Device to record readings from the probe.
- **Protective Casing**: To safeguard exposed parts of the probe and cable.
- **Backfill Soil**: Soil removed during drilling, to be used for refilling.
- **Water Container** (if required): For moistening soil, if it is too dry for drilling.

3. Site Preparation

Site Selection:

- Choose a location representative of the soil conditions to be studied.
- Avoid areas with obstructions such as large rocks or tree roots, which could interfere with drilling or probe placement.

Soil Moisture Check:

- Ensure the soil is adequately moist for easy drilling and good contact with the probe. Pre-moisten dry soil if necessary.

4. Installation Steps

Step 1: Drilling the Borehole

- **Select the Correct Auger Size**: Ensure the diameter of the auger matches the probe size for a snug fit.
- **Drill to the Required Depth**: Drill vertically to the target depth, typically between 30 cm and 1 meter, depending on the soil layers being monitored.
- **Ensure Vertical Alignment**: Make sure the borehole is straight and vertical to prevent probe damage during insertion.

Step 2: Inserting the Probe

- **Check the Probe**: Ensure that the sensors are clean and undamaged.

- **Careful Insertion**: Lower the probe gently into the borehole, making sure it is vertical and in contact with the soil to avoid air gaps, which can distort readings.
- **Backfill the Borehole**: Use the excavated soil to carefully refill the hole around the probe, ensuring the soil is packed tightly to maintain sensor contact.

Step 3: Securing the Probe

- **Protect Exposed Components**: If the probe has exposed cables, use protective casings to shield them from environmental factors.
- **Mark the Location**: Record the installation location using GPS or visible markers for easy retrieval.

5. Data Logging and Setup

Step 1: Connecting the Probe to the Data Logger

- **Secure Connection**: Attach the probe's cable to the data logger. Ensure the connection is firm and weatherproof, if necessary.
- **Power on the Logger**: Turn on the device and check for active readings from the sensors.

Step 2: Configuring Data Collection Settings

- **Set Sampling Intervals**: Adjust the data logger to record readings at intervals suited to your study objectives (e.g., every 15 minutes, hourly, or daily).
- **Test Initial Readings**: Collect a set of initial readings to ensure the sensors are functioning correctly.

Step 3: Data Storage and Monitoring

- **Download Data**: Periodically download data from the logger if it's not connected to a remote system.
- **Wireless Systems**: If using a wireless logger, monitor the system's connectivity to avoid data loss.

6. Maintenance and Troubleshooting

- **Regular Checks**: Periodically inspect the probe and logger for any physical damage, especially after extreme weather conditions.
- **Recalibration**: Recalibrate the probe if the readings show signs of drift or inconsistencies.

- **Data Backup**: Ensure data is backed up regularly, especially in cases of non-wireless loggers.

Troubleshooting:

- **No Data from Probe**: Check all cable connections and ensure the logger has sufficient power. If the probe is not registering, inspect for physical damage and reinstall if necessary.
- **Inconsistent Readings**: Check for loose contact with soil, air gaps, or sensor malfunction. Tighten the backfill and recalibrate the system if needed.

Drill & Drop Technical Specifications

All sensors and electronics are encapsulated within the probe rod. The probe rod cannot be disassembled, apart from accessing the battery in the top cap.

A probe can accumulate about 2000 samples/reading before the oldest readings are over written. This should be over 30 days with 30 minute samplings.

Bluetooth Requirements: 4.0 or later (Bluetooth Low Energy)

Sensors are measured starting from the top sensor (5cm, 15cm, 25cm etc.)

Moisture Sensor Resolution: 1:10000

Moisture Sensor Precision: ±0.03% vol.

TriSCAN Sensor Resolution: 1:6000

Temperature Sensor Accuracy: ±2 Deg. C @ 25 Deg C.

Temperature Sensor Resolution: 0.3 Deg C.

Temperature range (operating): -20 Deg C to +60 Deg C.

Voltage Supply: High Current 3.6V Lithium-ion "AA" Cell

Note: For reliable operation a 1.5V lithium cells are not suitable.

Battery life: 3.5 Years of continuous operation ** With a 120cm/4Ft TriSCAN probe using the default 30 minute sample interval and 2 downloads per day from one mobile device.

4. Model input and boundary conditions

5.1 About Hydrus 1D

HYDRUS-1D is a sophisticated Windows-based modeling environment designed for analyzing water flow and solute transport in variably saturated porous media. This software package features the one-dimensional finite element model HYDRUS, which simulates the movement of water, heat, and multiple solutes through heterogeneous soil profiles.

Key Features:

The software includes an interactive, graphics-based interface that simplifies data preprocessing and discretization of the soil profile. This user-friendly interface allows for effective visualization of soil structures and enables easy setup of simulation parameters. Additionally, HYDRUS-1D provides comprehensive graphical presentations of results, making data analysis intuitive.

Applications:

HYDRUS-1D is widely used in environmental science, agriculture, and hydrology for tasks such as optimizing irrigation practices, assessing groundwater quality, and studying contaminant transport. By accurately modeling the interactions between water, solutes, and soil, it plays a crucial role in developing sustainable land and water management practices.

In summary, HYDRUS-1D is an essential tool for researchers and practitioners interested in understanding soil-water interactions and improving water management strategies. (Pc-progress, 2008)

5.2 Main Processes

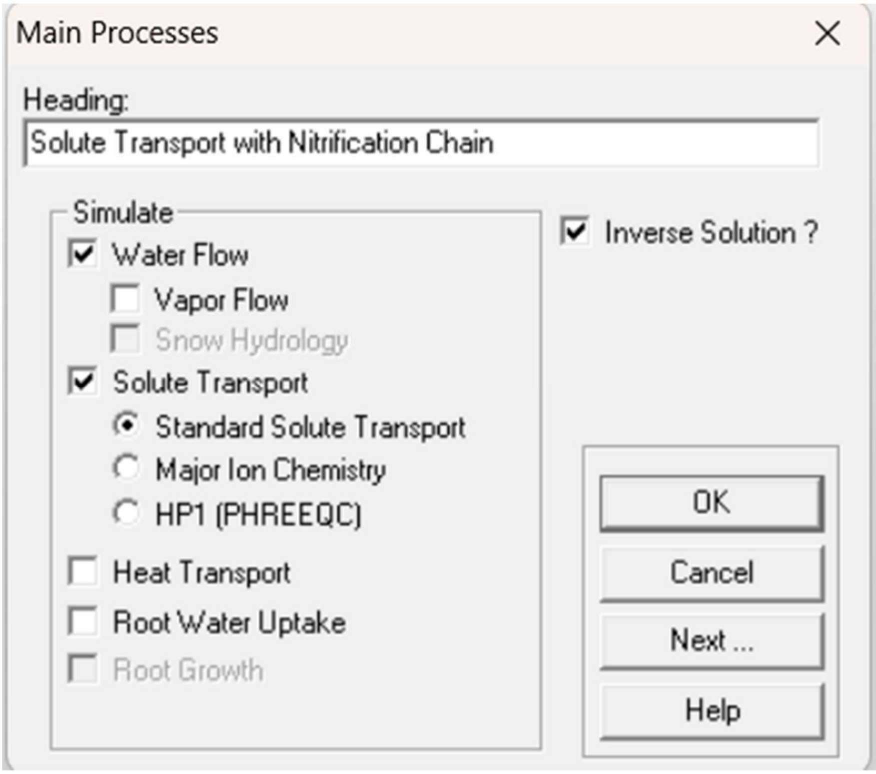


Figure 11. Main processes

The program automatically considers transient flow when the "water flow" option is selected; the initial condition for the pressure head is assumed to be constant during the calculation when the "water flow" option is not selected.

If the solute transport, heat transport or root water uptake options originally considered in an existing project, are switched off by the user, the program issues a warning that the data about these processes will be lost. If this loss is undesirable (it is), we recommend that you first copy the input data of the current project to a new project before switching off the solute transport, heat transport and/or root water uptake options.

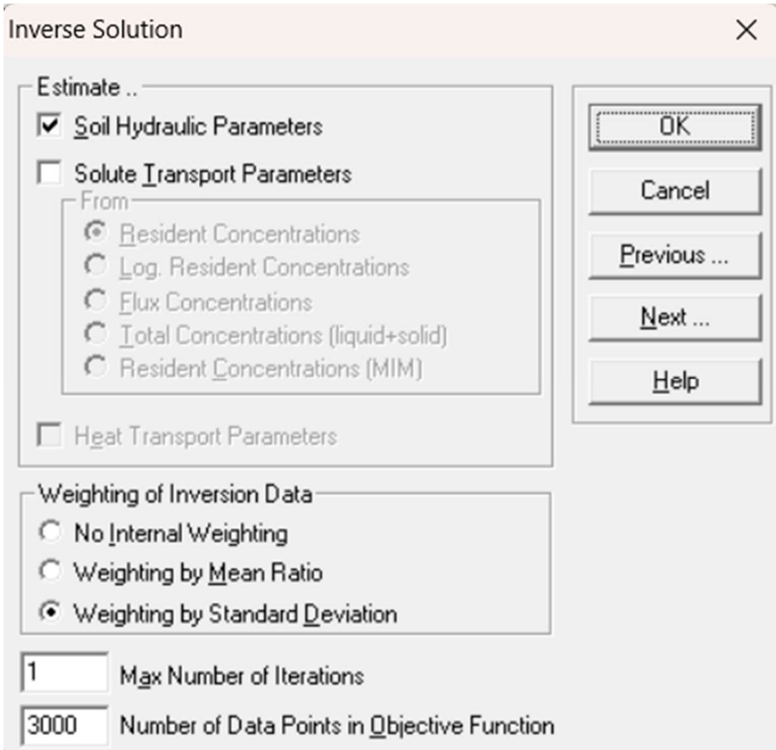


Figure 12. Inverse Solution tab.

The user selects whether or not the soil hydraulic and/or solute transport and reaction parameters are to be estimated from specified measured data using inverse procedures. One also selects the method of weighting of the data in the objective function. The user can choose between no weighting, weighting by mean ratios, or weighting by standard deviations. We chose Weighting by Standard Deviation for both fields.

Users can also select different concentration modes that can be used in the objective function. The choice is between:

a. resident liquid phase concentration (only mobile phase),
b. log resident liquid phase concentration,
c. flux concentration,
d. total concentration (includes both liquid and solid phase concentrations), and
e. total resident liquid phase concentration (includes both mobile and immobile phases).

The maximum number of iterations for the inverse solution is also specified. If one selects zero then only the direct simulation is carried out (Hopmans, Šimůnek, Romano, & Durner, 2002). In our case Max Number of Iterations is 1 for both fields and Number of data points in objective function is 3000 for the Gualdo columns.

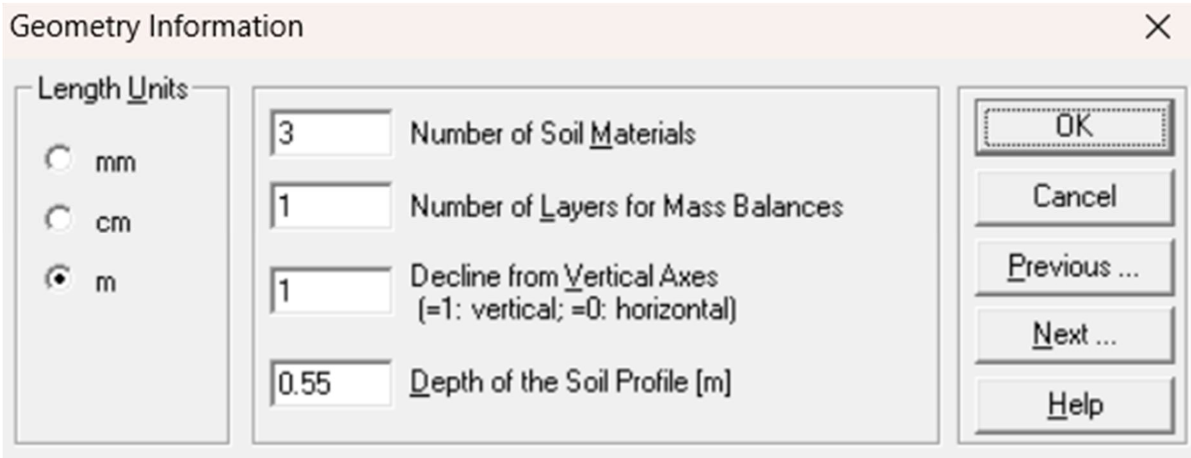


Figure 13. Geometry Information

Length Unit	Selects the length unit to be used throughout the application (mm, cm, m). When units are changed during or after reading all input data, then all variables are converted into the new units. We selected meters(m) for length unit for further work in the program.
Depth of the Soil Profile	Specifies the depth of the soil profile used later in the PROFILE module for discretization and specification of initial conditions and the domain property distribution. In Gualdo field depth of the Soil Profile is 0.55m
Number of Materials	Number of soil materials to be specified for the flow system. Materials are identified by material numbers, which are specified in the PROFILE module. The actual soil hydraulic and solute transport properties for each material are specified later in the application. Number of Soil Materials is 3
Number of Subregions	Number of subregions for which separate water and solute balances are being computed. Subregions are identified by subregion numbers, which are specified in the PROFILE module.
Decline from Vertical	Allows a user to choose between a vertical and/or horizontal soil profile. Any inclined direction of the soil profile is allowed. The inclination is specified in terms of the cosine of the angle between the

vertical axis and the axis of the soil profile. Its value is equal to one for vertical soil columns and zero for horizontal soil columns.

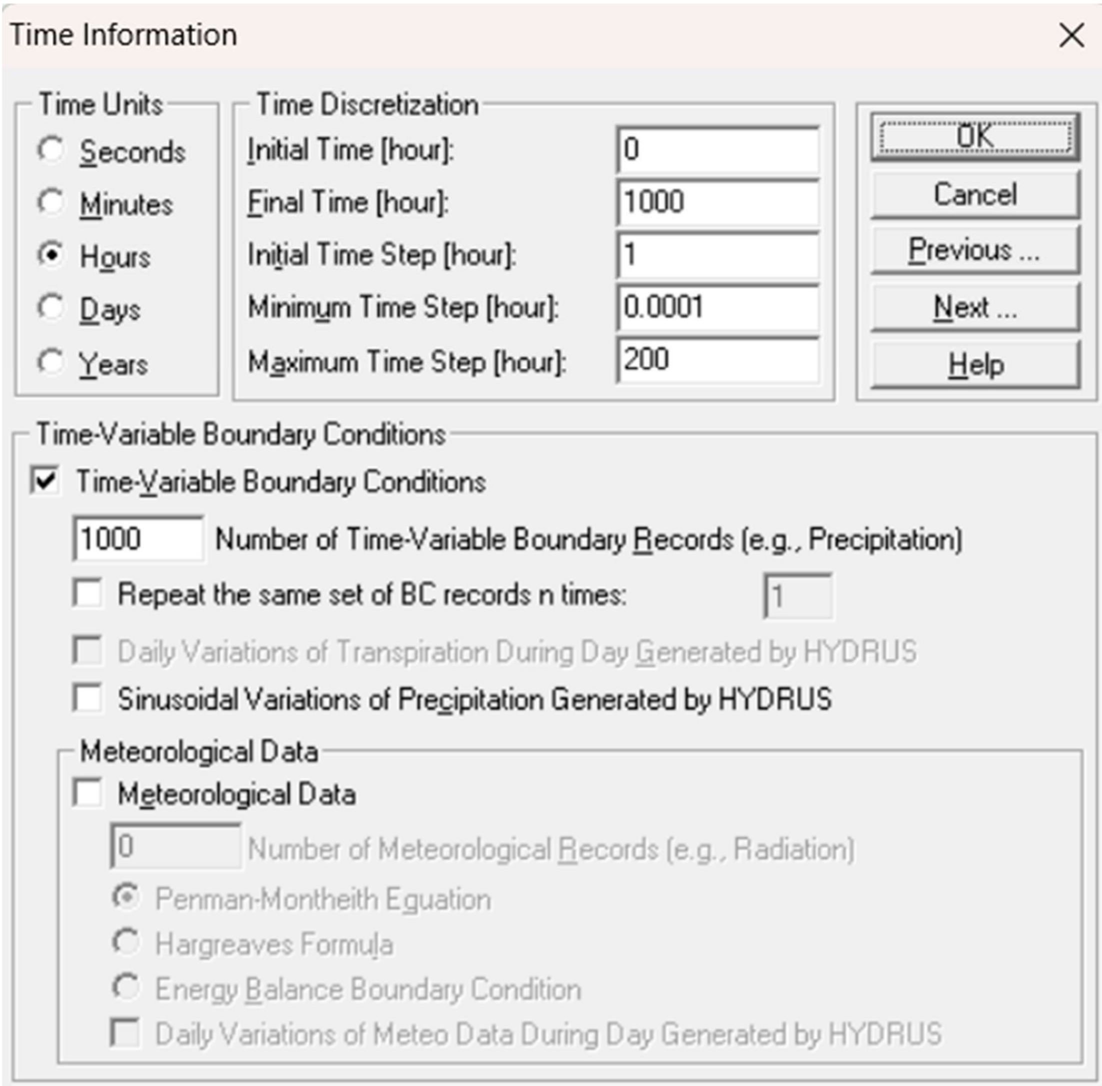


Figure 14. Time Information

Time Unit — Selects the time unit to be used throughout the application (days, hours, min, sec). When units are changed during or after reading the input data, then all variables are converted into the new units. Days are selected as Time units.

Time Discretization	Specifies the main time variables governing the time discretization.
Initial Time	Starting time of the calculation [T].
Final Time	Final time of the calculation [T]. Final time is a total number of days of the experiment and it is 41 days.
Initial Time Step	Initial time increment, *dt* [T]. The recommended value for the initial time step depends on the type of simulation and boundary conditions used. When simulating a process that starts with a large initial pressure head or concentration gradient at the boundary (e.g., ponded infiltration or a sudden change of boundary concentration), use a small value of the initial time step (e.g., 1 s). When simulating a long term process with variable boundary conditions (e.g., seasonal or multiyear simulation), start with a larger time step (e.g., 15 min).
Minimum Time Step	Minimum permitted value of the time increment, dt_{min} [T].The minimum time step must be smaller than a) the initial time step, b) interval between print times, and c) interval between time-variable boundary condition records. Always specify a small minimum allowed time step, on the order of 1 s. This value may never be used, but it provides the code with flexibility when it may be needed, e.g., when there is a sudden change in boundary fluxes and HYDRUS may not converge with larger time steps.

Time-dependent boundary conditions - The number of time-dependent boundary records and associated time-dependent boundary conditions must be specified when this box is checked. Otherwise, boundary conditions are assumed to be constant in time.

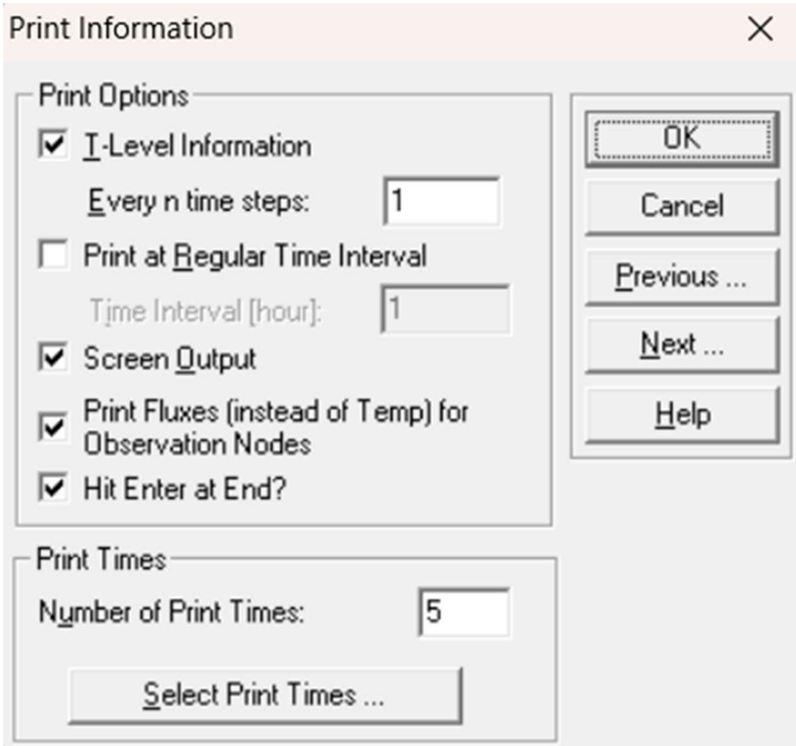


Figure 15: Print Information

Print Options	Variables governing the output from HYDRUS:
T-Level Information	Use this check box to decide whether certain information concerning the mean pressure head, mean water and solute fluxes, cumulative water and solute fluxes, and time and iteration information, are to be printed after each time step, or only at preselected times.
Time Interval Output	Alternatively, users can specify that the output is printed at regular specified time interval.
Screen Output	Use this check box to decide whether or not information about the simulation run is to be printed to the screen during execution of the HYDRUS code.
Print Fluxes for Observation Nodes	Use this check box if you want to print into the output for observation nodes water fluxes instead of temperatures.

Hit Enter at End	When this box is checked after the calculations are done, the DOS window remains open and waits for a command from the user (the Enter command) before it is closed and program returns to GUI. The DOS window automatically closes when this box is unchecked.
No. of Print Times	Number of specified print times at which detailed information about the pressure head, water content, concentration, water and solute fluxes, and soil-water and solute balances will be printed.

The command Select Print Time calls the Print-Times dialog, in which a user can specify printing time at which detailed information about the pressure head, water content, concentration, water and solute fluxes, and soil-water and solute balances will be printed.

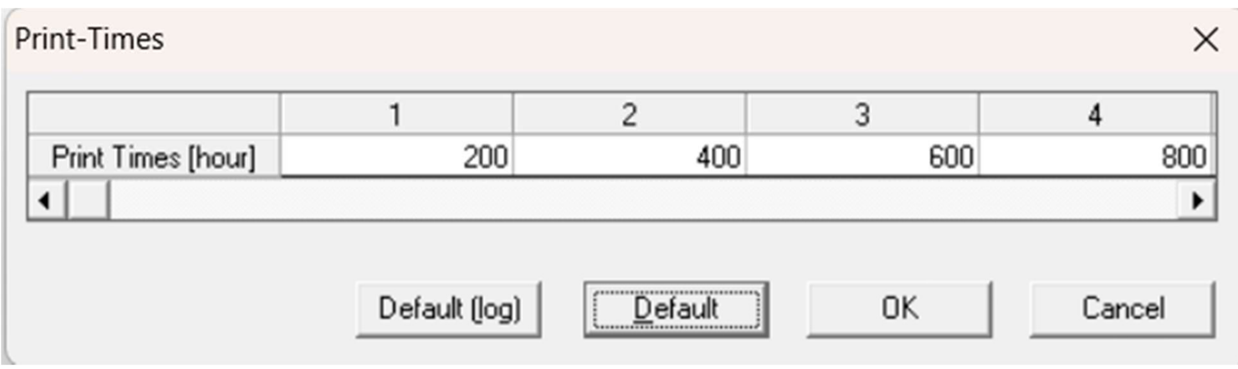


Figure 16. Print-Times

Clicking on the Default command redistributes Print-Times at equal time intervals. Clicking on the Default (log) command redistributes Print-Times at logarithmically increasing time intervals.

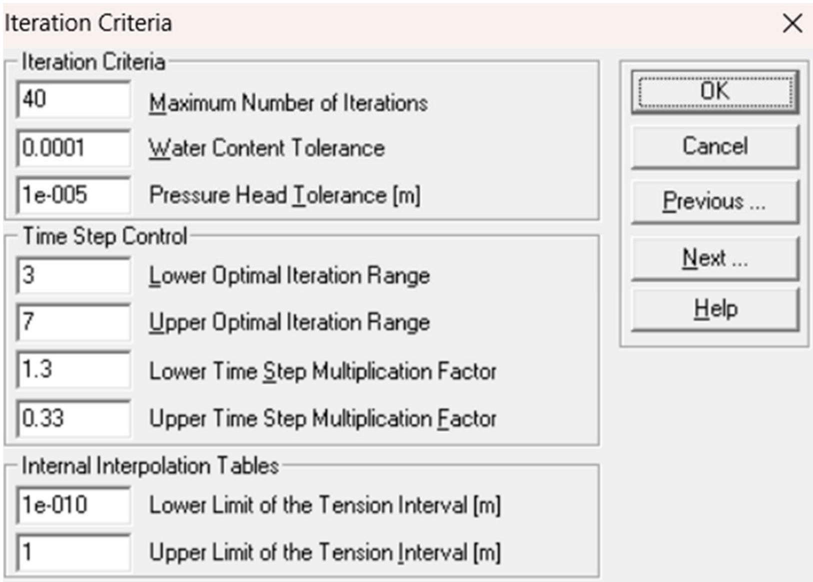


Figure 17. Iteration Criteria tab.

Iteration Criteria	Specifies iteration criteria for the solution precision.
Time Step Control	Specifies parameters for controlling the time step.
Internal Interpolation Tables	Specifies limits for internal interpolation tables

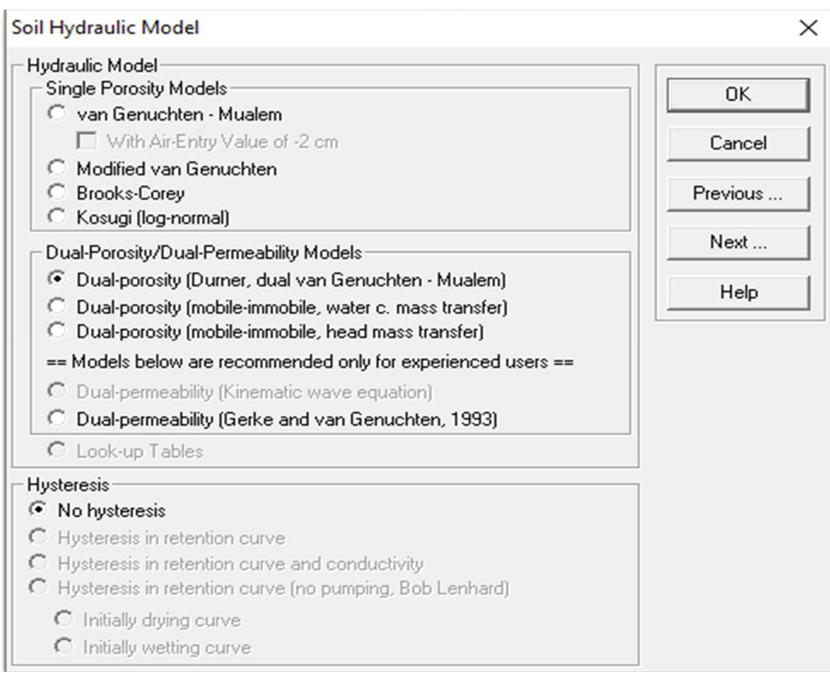


Figure 18. Soil Hydraulic Model tab.

In the Soil Hydraulic Model dialog window user select the Hydraulic Model to be used for the soil hydraulic properties, and specify whether or not Hysteresis is to be considered during the calculations. Hydraulic Model:

The code allows users to select six types of models for the soil hydraulic properties.

Hysteresis: When the van Genuchten model is used, either a) a non-hysteretic description (*No Hysteresis*), b) a hysteretic description only in the retention curve (*Hysteresis in Retention Curve*), or c) hysteretic descriptions in both the retention curve and the hydraulic conductivity curve (*Hysteresis in Retention Curve and Conductivity*) can be used (Kool & Parker, 1987).

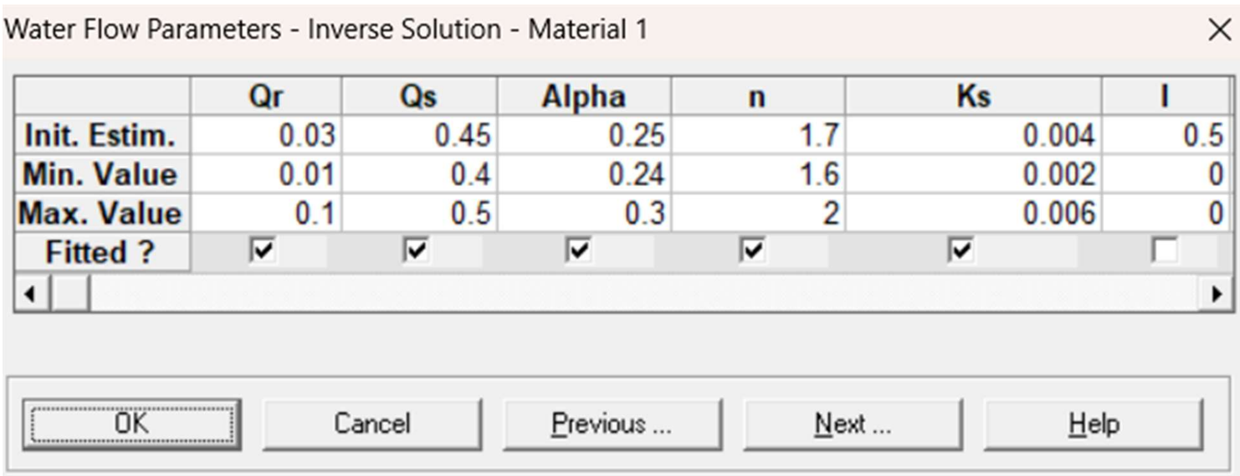


Figure 19. Water Flow Parameters for material 1.

When the parameter estimation option is selected, then the user has to provide initial estimates of the optimized soil hydraulic parameters, specify which parameters are to be optimized, and provide parameter constraints for the optimization (Vogel & Cislerova, 1988).

Qr	Residual soil water content, θ_r
Qs	Saturated soil water content, θ_s
Alpha	Parameter α in the soil water retention function [L^{-1}]
n	Parameter *n* in the soil water retention function
Ks	Saturated hydraulic conductivity, K_s [LT^{-1}]
l	Tortuosity parameter in the conductivity function [-]

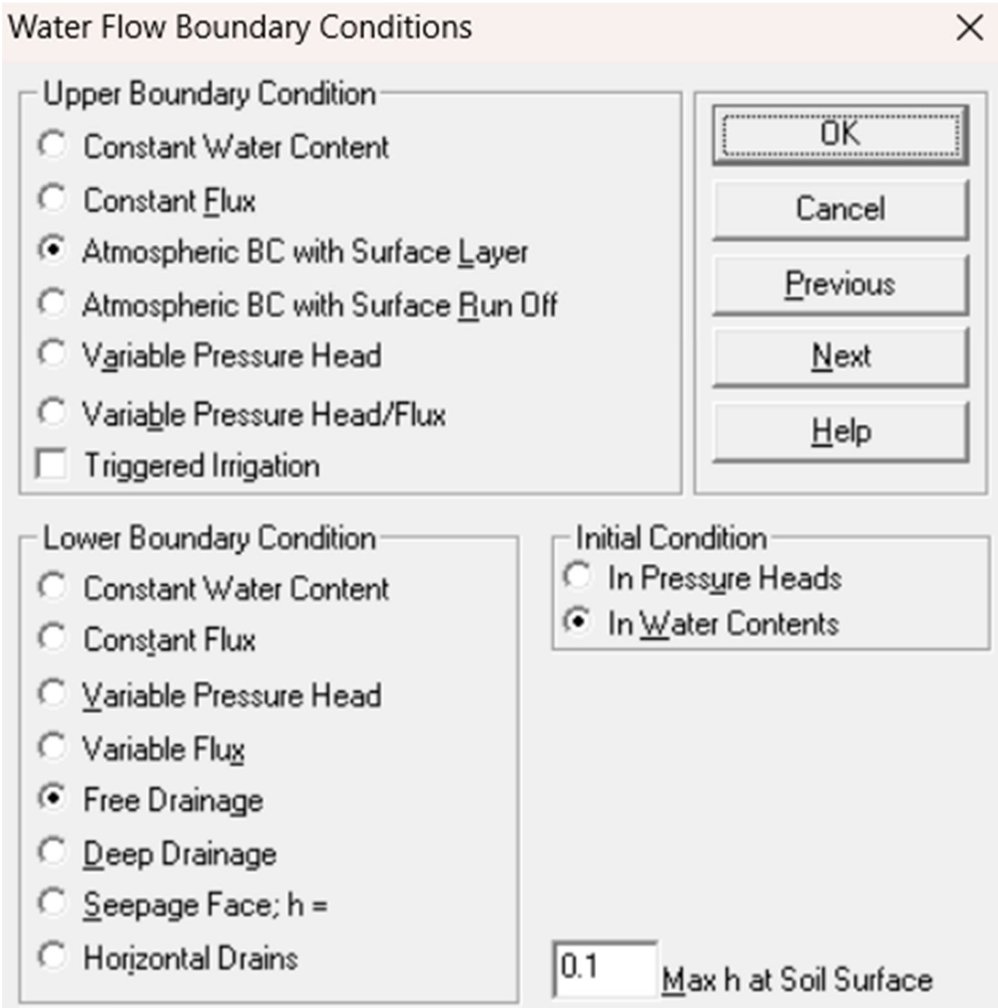


Figure 20. Water Flow Boundary Conditions tab.

The user specifies the type of upper and lower boundary conditions to be used.
Initial Conditions.
The initial condition can be specified either in terms of the pressure head or the water content.

Atmospheric BC

Input PET and LAI: Instead of entering atmospheric fluxes (i.e., potential evaporation and transpiration fluxes), separately, it is also possible to enter a combined value of potential evapotranspiration and separate potential evaporation and transpiration fluxes based on LAI and the extinction coefficient. One may also specify the maximum thickness of the surface water layer (Max h at Soil Surface) before surface runoff is initiated.

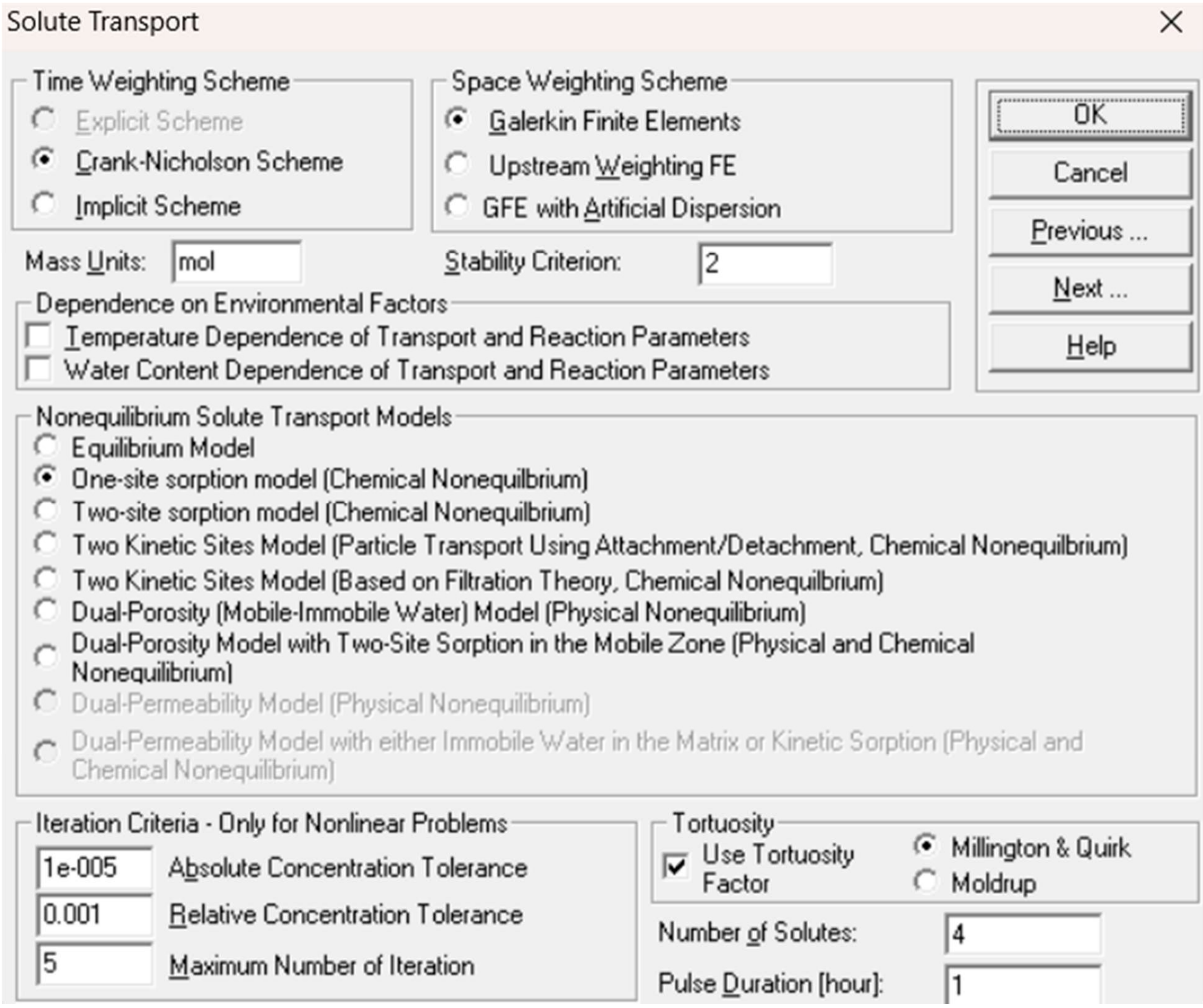


Figure 21. Solute Transport tab.

The Crank-Nicholson implicit scheme is recommended in view of solution precision. The fully implicit scheme may result in excessive numerical dispersion, but avoid numerical instabilities. The explicit scheme is most prone to numerical instabilities with undesired oscillations.

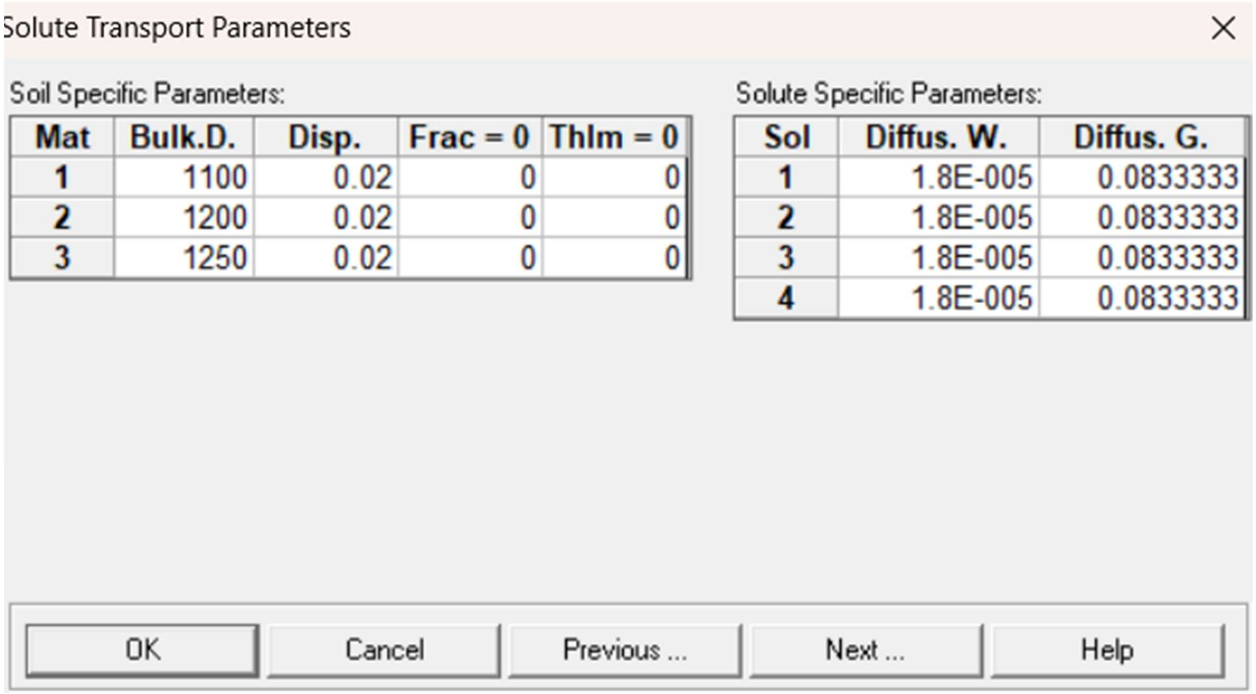


Figure. 22 Solute Transport Parameters tab.

This command specifies solute transport parameters for each soil material:
Soil Specific Parameters:

Bulk.d.	Bulk density, $[ML^{-3}]$
Disp	Longitudinal dispersivity, D_L [L]
Frac	Dimensionless fraction of adsorption sites classified as type-1, i.e., sites with instantaneous sorption when the chemical nonequilibrium option is considered [-]. Set equal to 1 if equilibrium transport is considered. Dimensionless fraction of adsorption sites in contact with mobile water when physical nonequilibrium is considered [-]. Set equal to 1 if all sorption sites are in contact with mobile water.
ThImob	Immobile water content. Set equal to 0 when physical nonequilibrium is not considered. ThImob (when >0) is interpreted as a water content, from which particles (e.g., viruses, colloids, bacteria) are excluded when the Two Kinetic Sites Model is used.

Solute Specific Parameters:

Diffus.W	Molecular diffusion coefficient in free water, D_w $[L^2T^{-1}]$
Diffus.G	Molecular diffusion coefficient in soil air, D_a $[L^2T^{-1}]$

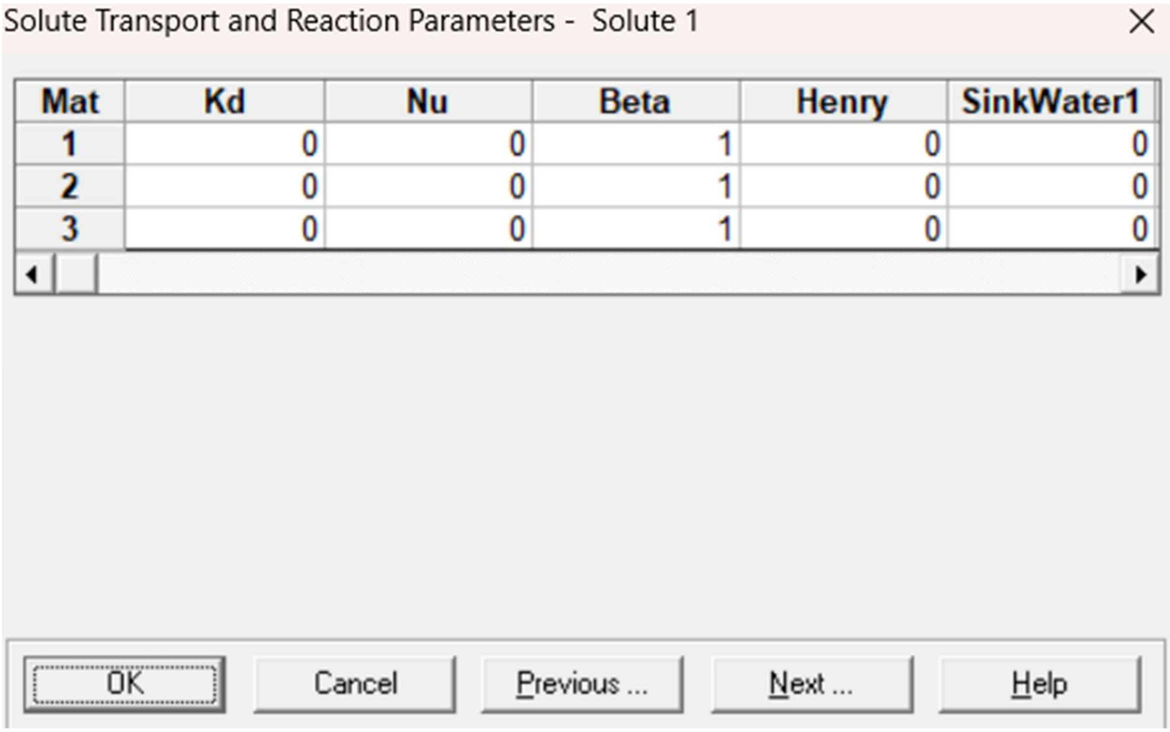


Figure 23. Solute Transport and reaction parameters tab.

This command specifies solute reaction parameters for each soil material:

Kd	Adsorption isotherm coefficient, k_s [$M^{-1}L^3$]
Nu	Adsorption isotherm coefficient, ν [$M^{-1}L^3$] (referred to as η in the manual, the Langmuir coefficient)
Beta	Adsorption isotherm coefficient, β [] (the Freundlich exponent)
Henry	Equilibrium distribution constant between liquid and gaseous phases, k_g []
SinkWater1	First-order rate constant for dissolved phase, μ_w [T^{-1}]
SinkSolid1	First-order rate constant for solid phase, μ_s [T^{-1}]
SinkGas1	First-order rate constant for gas phase, μ_g [T^{-1}]
SinkWater1'	First-order rate constant for dissolved phase, μ_w' [T^{-1}], representing the chain reaction
SinkSolid1'	First-order rate constant for solid phase, μ_s' [T^{-1}], representing the chain reaction
SinkGas1'	First-order rate constant for gas phase, μ_g' [T^{-1}], representing the chain reaction
SinkWater0	Zero-order rate constant for dissolved phase, γ_w [$ML^{-3}T^{-1}$]
SinkSolid0	Zero-order rate constant for solid phase, γ_s [T^{-1}]
SinkGas0	Zero-order rate constant for solid phase, γ_g [$ML^{-3}T^{-1}$]
Alpha	First order rate coefficient for one site or two site nonequilibrium adsorption, mass transfer coefficient for solute exchange between mobile and immobile liquid regions, ω[T^{-1}]

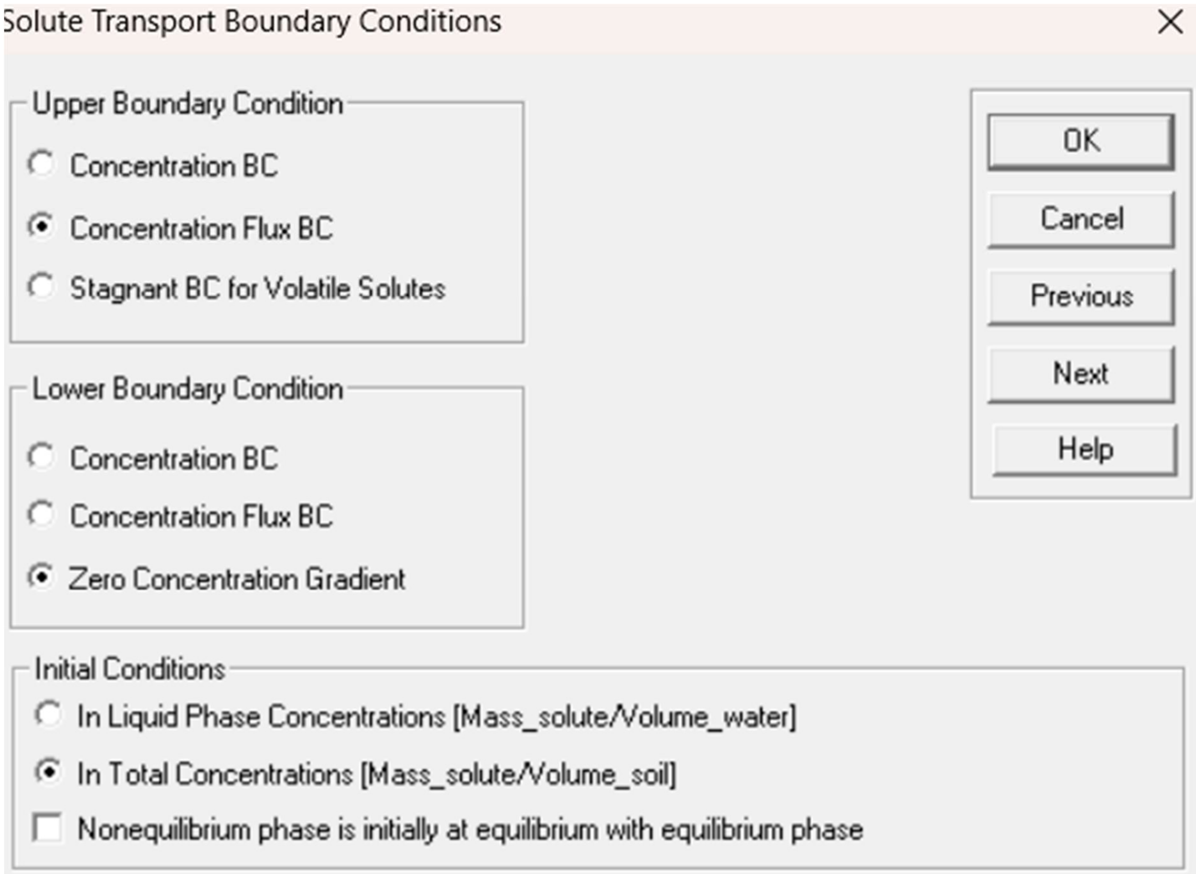
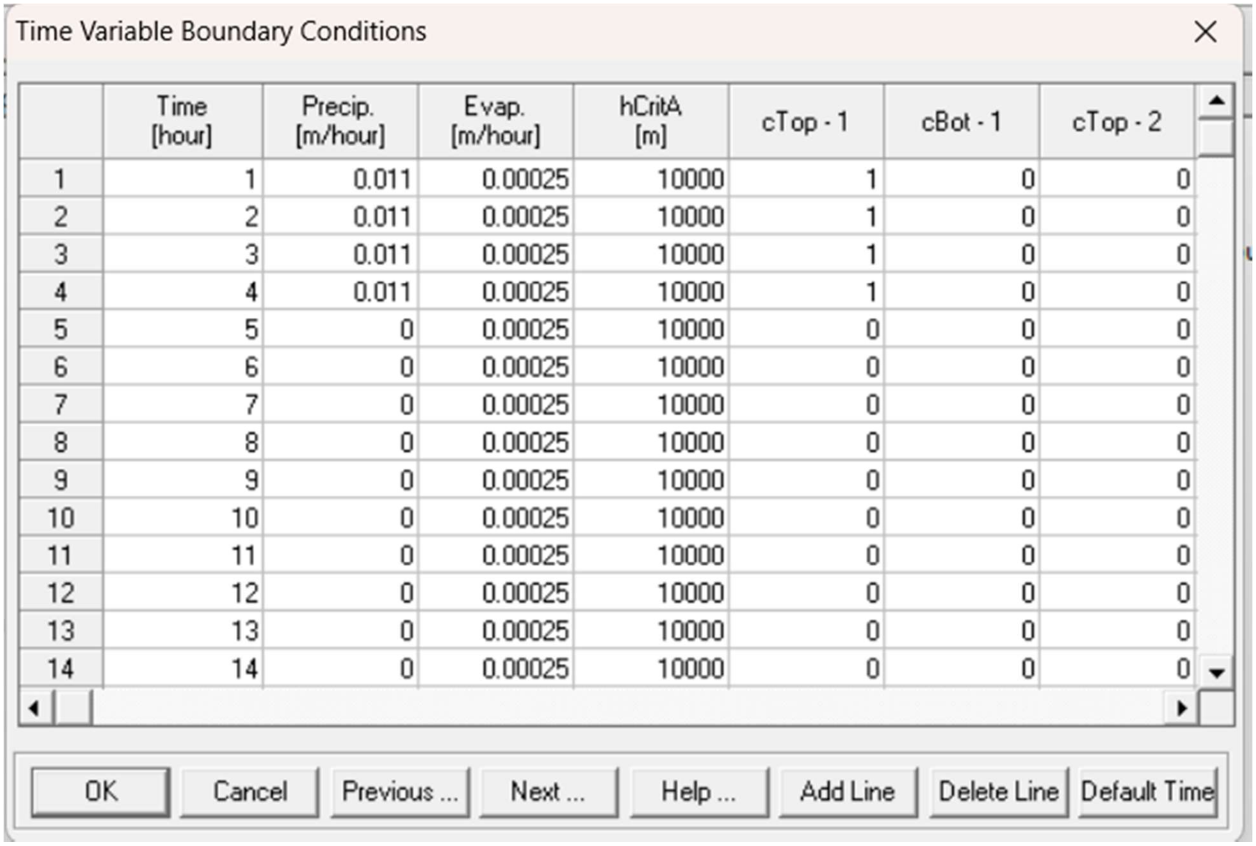


Figure 24: Solute Transport Boundary Conditions tab.

Concentration flux BC is selected as Upper boundary condition, Zero concentration gradient is selected for Lower boundary condition and Initial conditions are selected In liquid phase concentrations, for both sites.



	Time [hour]	Precip. [m/hour]	Evap. [m/hour]	hCritA [m]	cTop - 1	cBot - 1	cTop - 2
1	1	0.011	0.00025	10000	1	0	0
2	2	0.011	0.00025	10000	1	0	0
3	3	0.011	0.00025	10000	1	0	0
4	4	0.011	0.00025	10000	1	0	0
5	5	0	0.00025	10000	0	0	0
6	6	0	0.00025	10000	0	0	0
7	7	0	0.00025	10000	0	0	0
8	8	0	0.00025	10000	0	0	0
9	9	0	0.00025	10000	0	0	0
10	10	0	0.00025	10000	0	0	0
11	11	0	0.00025	10000	0	0	0
12	12	0	0.00025	10000	0	0	0
13	13	0	0.00025	10000	0	0	0
14	14	0	0.00025	10000	0	0	0

Figure 25. Time variable boundary conditions tab.

Those data were measured in the sites where often precipitation of 44 mm every 4 hours have been observed as extreme weather events and measured evaporation of 0.25 mm per hour were typical of laboratory conditions. Inserted there is also the fluorescent tracer concentrate in the first 4 hours.

Time	Time for which a data record is provided [T]. Boundary condition values are specified for the time interval preceding time given at the same line. Thus BC values specified in the first row are for the time interval between the initial time and time specified on the same line.
Precip	Precipitation rate [LT^{-1}] (in absolute value).
hCritA	Absolute value of the minimum allowed pressure head at the soil surface [L].
GWL	Groundwater level [L], or other time-dependent prescribed head boundary condition; set equal to zero when no time-dependent head boundary condition is specified.

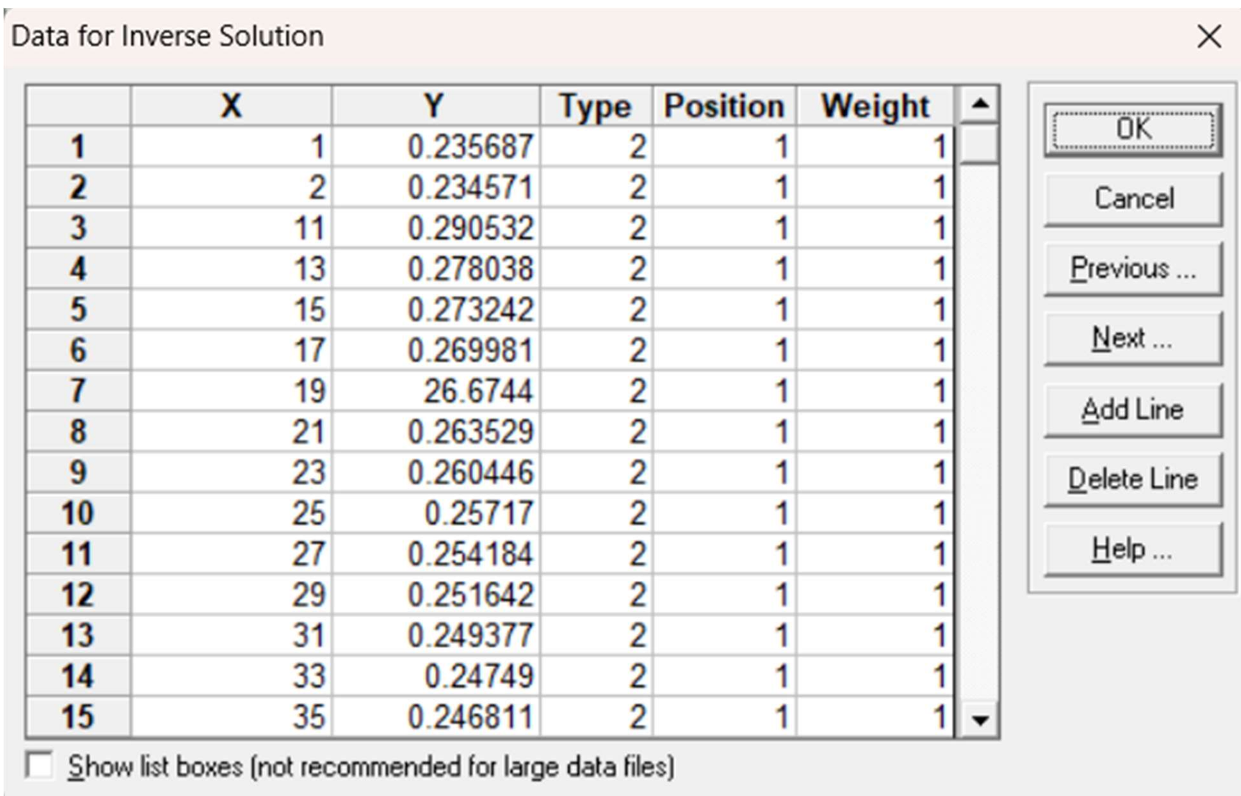
cTop	Time-dependent concentration at the soil surface boundary. When the solute flux is used as the boundary condition, then cTop is the solute concentration of the incoming water (do not specify if solute transport is not considered or when no time variable boundary conditions are used).
	
	Note that the cTop value is adjusted as follows:
	
	if((Precip-Evap).gt.0.) then
	
	cTop =Precip/(Precip-Evap)*cTop
	
	else if(Evap.gt.0.) then
	
	cTop =0.
	
	end if
	
	where Precip is the precipitation and Evap is evaporation, to account for the effects of upward (Precip) and downward (Evap) fluxes on concentration of infiltrating water.

cBot (cRoot)	Time-dependent concentration at the lower boundary. When the solute flux is used as the boundary condition then cBot is the solute concentration of the incoming water (do not specify if solute transport is not considered or when time variable boundary conditions are used). When the active solute uptake is considered, then this column is used to specify the *Potential Solute Uptake Rate* [$ML^{-2}T^{-1}$]).

Inverse solution

Parameter optimization is an indirect method used to estimate soil hydraulic and solute transport parameters from transient flow or transport data. This approach involves minimizing an objective function that quantifies the difference between observed data and the system's predicted response. The unknown parameters describing soil hydraulic properties are typically represented by an analytical model, while the system's response is derived from a numerical solution of the flow equation, incorporating parameterized hydraulic functions, transport parameters, and relevant initial and boundary conditions.

To refine these unknown parameters, initial estimates are iteratively adjusted during the minimization process until a satisfactory level of accuracy is achieved. Originally, this technique was applied to analyze one-step and multi-step column outflow data collected in laboratory settings, as well as transport data from both laboratory and field experiments under steady-state water flow conditions (Van Genuchten, 1981; Toride et al., 1995). The HYDRUS software now includes capabilities for parameter optimization, allowing it to estimate solute transport and reaction parameters from transient water flow and solute transport experiments.



	X	Y	Type	Position	Weight
1	1	0.235687	2	1	1
2	2	0.234571	2	1	1
3	11	0.290532	2	1	1
4	13	0.278038	2	1	1
5	15	0.273242	2	1	1
6	17	0.269981	2	1	1
7	19	26.6744	2	1	1
8	21	0.263529	2	1	1
9	23	0.260446	2	1	1
10	25	0.25717	2	1	1
11	27	0.254184	2	1	1
12	29	0.251642	2	1	1
13	31	0.249377	2	1	1
14	33	0.24749	2	1	1
15	35	0.246811	2	1	1

Figure 26. Data for inverse solution tab.

Details about the definition of the objective function are given in this table. Type: = 1: Pressure head measurements at certain observation point(s).

Depending upon the value of the parameter *Type,* the first column contains the following information:

X**:**= time for *Type* = 0, 1, 2, 3, 4

Depending upon the value of parameter *Type,* the second column contains the following information:

Y***:*** = observation data

= average water content of the entire flow domain when *Type* = 2 and *Position* = 0.

= total solute amount in the entire flow domain when *Type* = 4 and *Position* = 0. Depending upon the value of parameter *Type*, the fourth column contains the following information:

Position := position of the observation node for *Type* = 1, 2, 4

Weight - weight associated with a particular data point (Šimůnek, van Genuchten, & Wendroth, 1998).

5. Results

6.1 Calibration procedure

Observations points pressure head

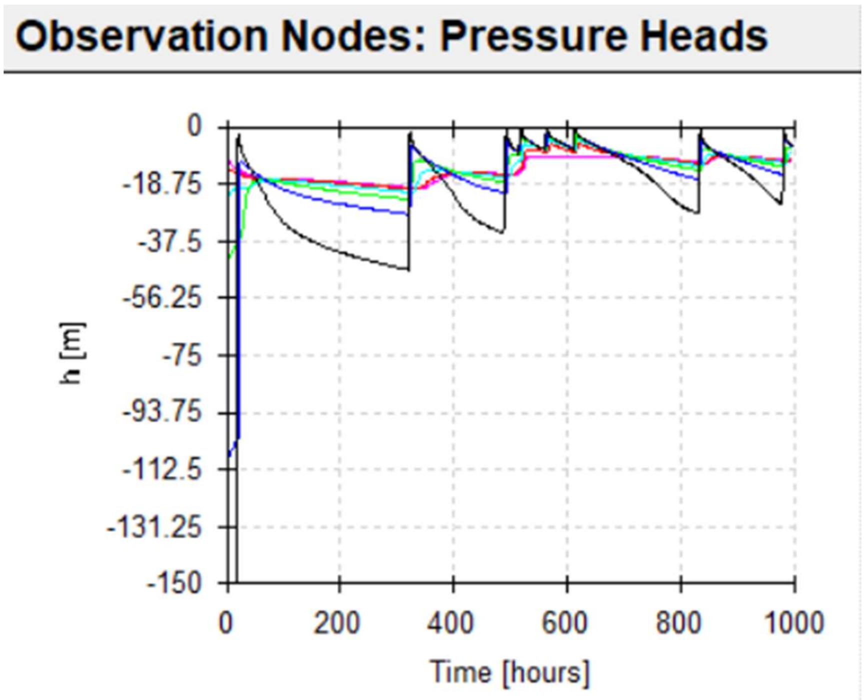


Figure 27. Pressure head

The graph in Figure 42 illustrates the variation in pressure head over time at six observation nodes (N1 to N6) within a soil profile, providing key insights into the hydraulic behavior of the system under study. Pressure head, expressed in meters, is plotted against time in hours, revealing distinct patterns at each node. Node N1 exhibits the most pronounced fluctuations, with its pressure head dropping sharply to nearly -100 meters around 10 hours, followed by a gradual recovery. In contrast, the other nodes (N2 to N6) display more moderate changes, fluctuating between approximately -50 meters and 0 meters. All nodes experience transient decreases in pressure head at key points—around 500, 800, and 1000 hours—indicating significant system events, possibly related to infiltration or changes in boundary conditions. Notably, the extreme behavior of N1 suggests that this node is either located in a more sensitive area of the profile or is subject to different external conditions compared to the others (-5 cm below ground level). Overall, this graph provides a comprehensive visualization of how pressure head evolves over time across different points in the system, offering crucial data for understanding soil-water dynamics in this experimental setup.

6.2 Observation nodes: Water content

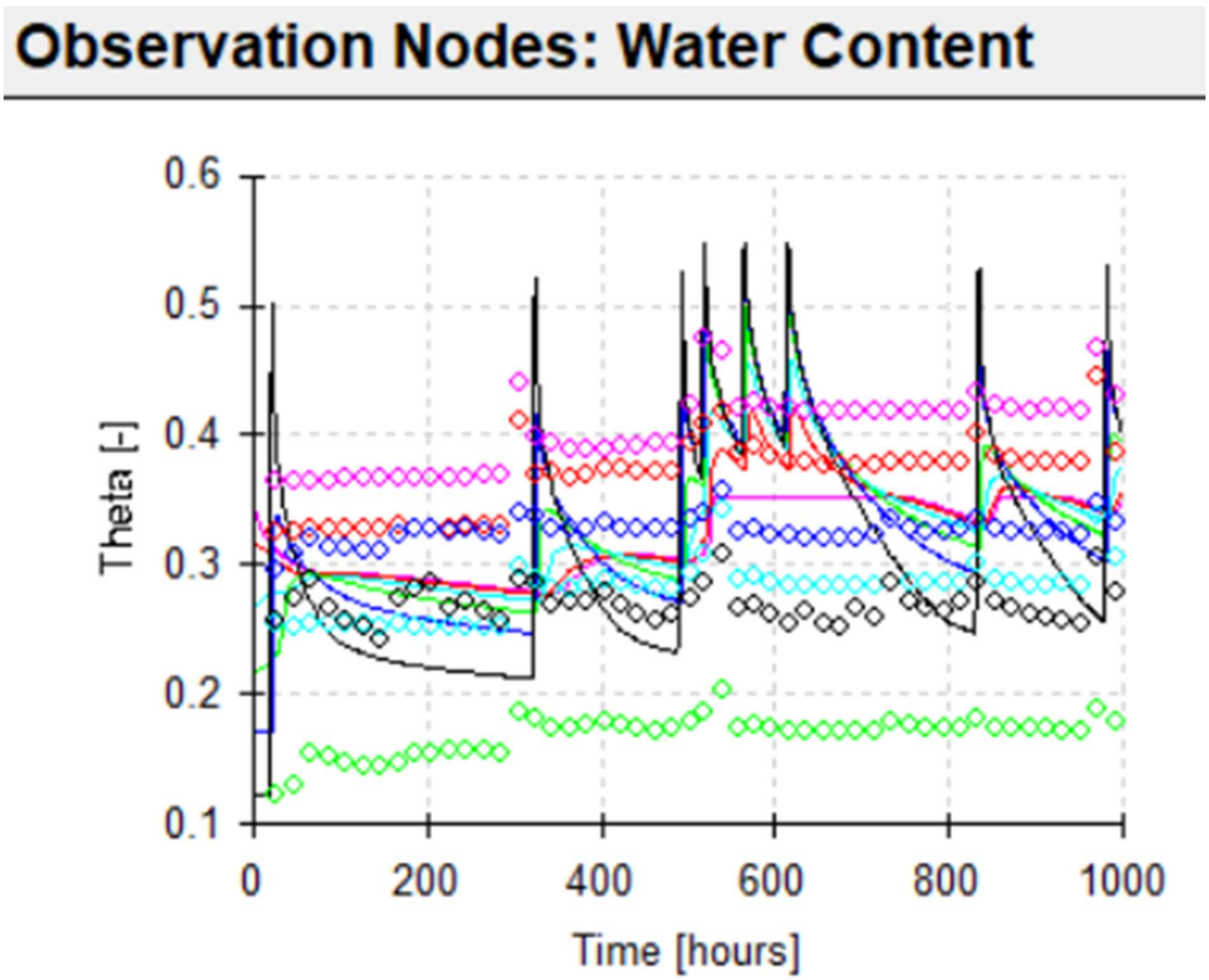


Figure 28. Water content observed (dots) and simulated (lines).

The graph in Figure 28 illustrates the temporal variation in water content (θ\thetaθ) at multiple observation nodes (N1 to N6) over a period of 1000 hours, providing critical insights into the moisture dynamics within the soil profile. Water content is displayed as a dimensionless ratio, where 1 represents saturation, and is plotted against time in hours. Throughout the experiment, the nodes exhibit distinct patterns in water content, reflecting the influence of both environmental conditions and soil properties.

At nodes N1 (black line), N2 (blue line), and N3 (green line), significant reductions in water content are observed around 400, 600, and 900 hours, indicating periods of increased water loss, potentially driven by evapotranspiration or drainage. These fluctuations suggest that these nodes are located in more vulnerable sections of the soil, where moisture is more easily depleted. In contrast, nodes N4 (cyan line), N5 (red line), and N6 (pink line) maintain relatively higher water content throughout the experiment, with values consistently above 0.3, implying that these nodes are situated in areas with better water retention, likely deeper within the soil or in less-stressed zones.

The transient decreases in water content observed at several points—particularly around 50, 650, and 850 hours—can be attributed to periods of drought or heightened plant water uptake. However, these drops are followed by recoveries in water content, suggesting subsequent recharge events, such as rainfall or irrigation. The stabilization of water content levels following these recovery phases highlights the soil's capacity to retain moisture once external conditions improve. Additionally, the smaller fluctuations observed in N4, N5, and N6 indicate that these nodes experience less stress due to their position within the soil profile, possibly benefiting from proximity to a deeper water source or less exposure to evaporation.

This graph offers valuable data on the soil-water dynamics at different depths and positions within the profile, essential for understanding how moisture is distributed and retained over time. The behavior of the water content at these observation nodes underscores the complexity of moisture movement within the soil, as well as the influence of external factors such as evapotranspiration and infiltration, critical for informing water management strategies in the field.

6.3 Observation nodes: Concentration

Figure 29 represents concentration profiles of urea over time, with measurements taken at three different depths: the black line at 5 cm below ground, the blue line at 15 cm, and the green line at 25 cm. These profiles help illustrate how each substance behaves as it moves through the soil over time.

Urea concentration profile:

- 5 cm depth (black line): Urea shows an immediate and sharp spike in concentration at this shallow depth, peaking close to 8 mol/m^3. This reflects the high solubility of urea, which rapidly dissolves and accumulates near the surface. This peak occurs within the first few hours after application, highlighting urea's quick uptake in the soil.
- 15 cm depth (blue line): The concentration at 15 cm also rises but with a much lower peak (around 2 mol/m^3) compared to the 5 cm depth. This shows that urea moves downward but less efficiently than at the surface, suggesting that it quickly disperses or is absorbed by plants before reaching deeper layers.
- 25 cm depth (green line): At 25 cm, urea concentration is minimal, with only a slight increase at the beginning. This indicates that urea penetration into the deeper layers is limited and occurs at a much slower rate, likely due to plant uptake or microbial processes in the upper layers.

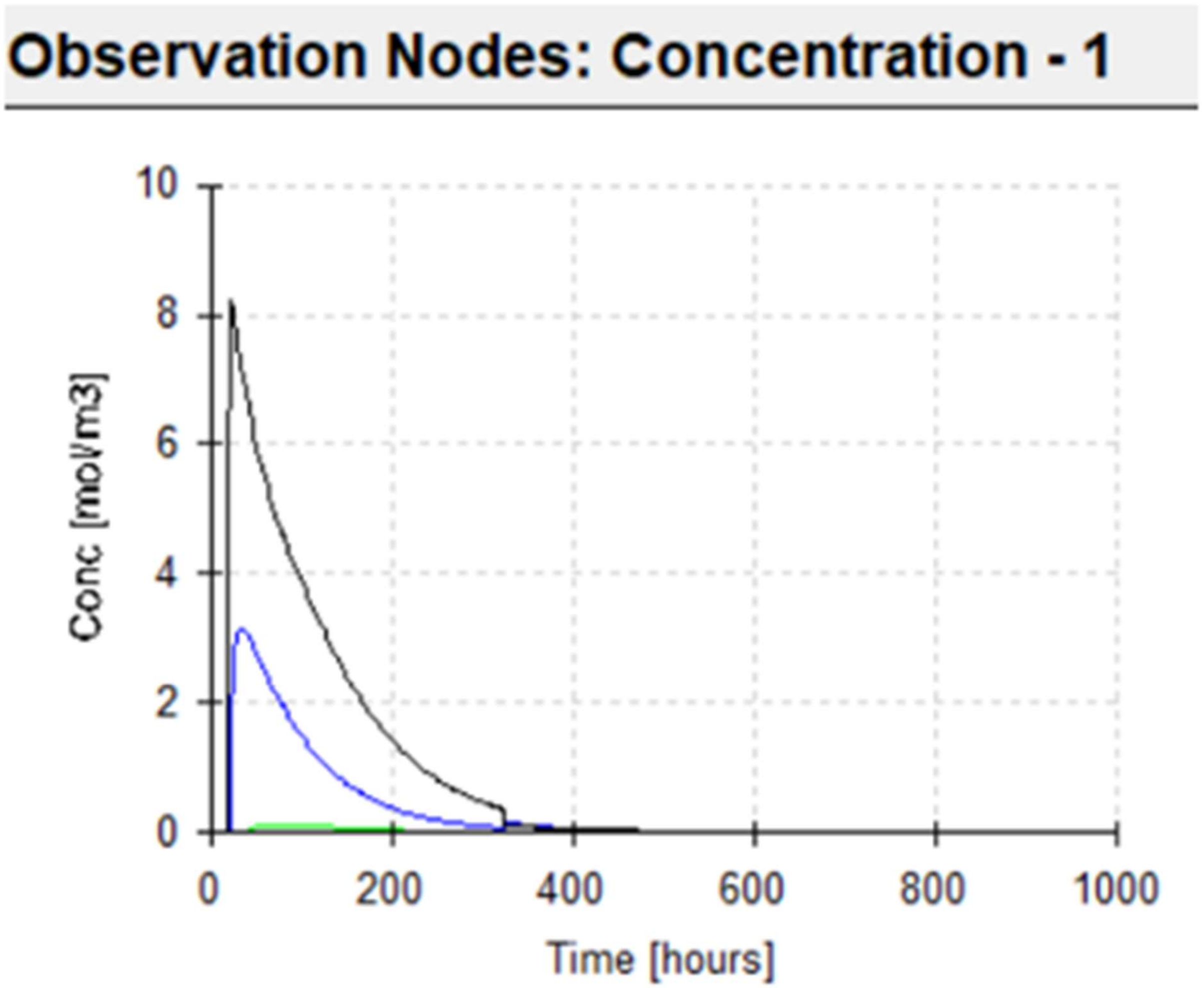


Figure 29. Concentration of Urea at 3 different depths.

Digestate concentration profile (Fig. 30):

- 5 cm depth (black line): The digestate shows a gradual rise in concentration at the shallow 5 cm depth, but its peak is much lower, around 1.5 mol/m³. Unlike urea, digestate releases its nutrients more slowly, as it consists of organic material that requires decomposition before becoming available to plants.
- 15 cm depth (blue line): At 15 cm, the digestate shows an even smaller peak compared to the 5 cm depth, indicating slower downward movement of nutrients through the soil. The

rise in concentration is more gradual, and the overall peak is much lower than at 5 cm, reflecting its slow breakdown.

- 25 cm depth (green line): At the deepest level (25 cm), digestate concentration remains very low, showing only a slight increase over time. This slow nutrient migration highlights the digestate's tendency to remain in the upper layers of the soil, decomposing gradually and releasing nutrients over a prolonged period.

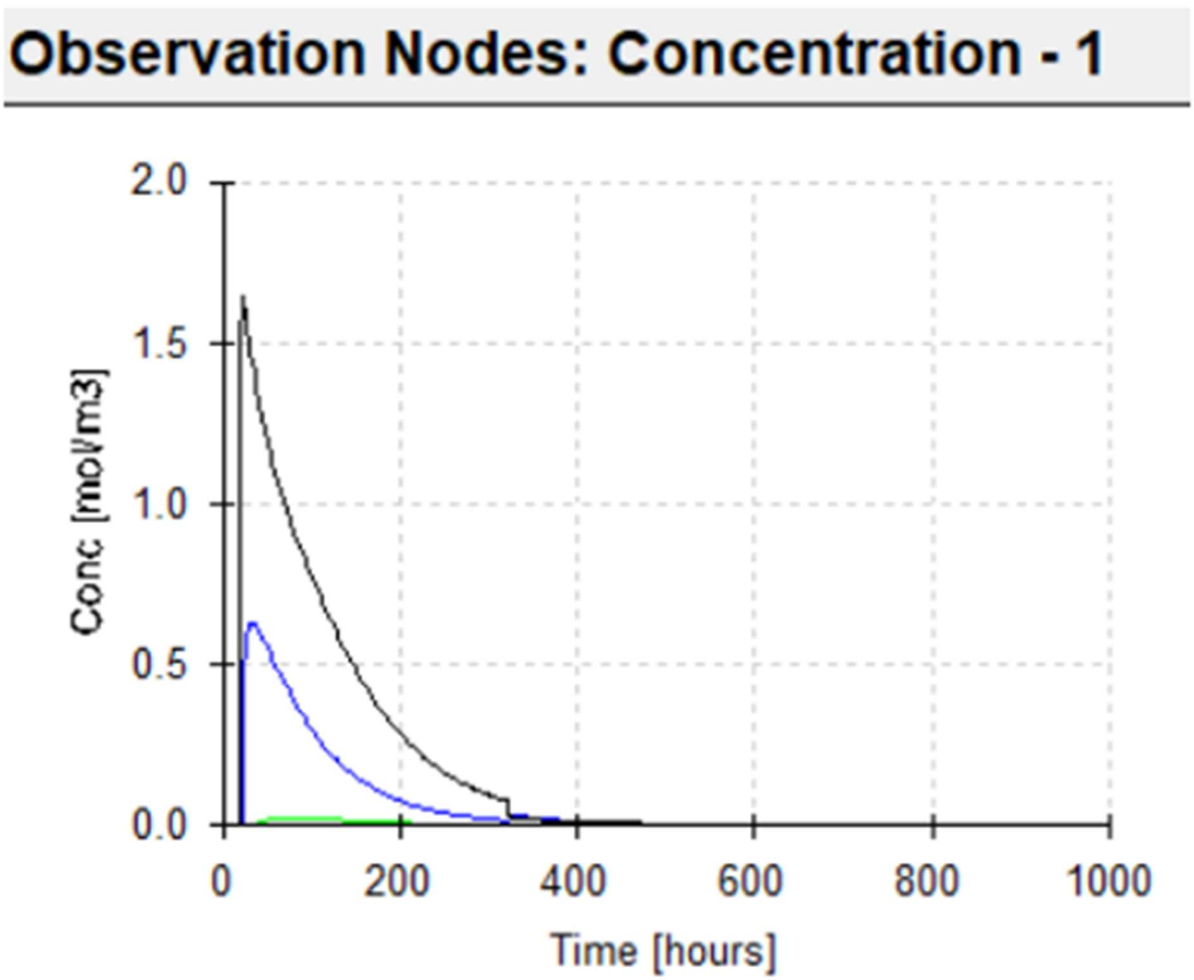


Figure 30. Concentration of Urea in the Digestate column.

Comparative differences: Urea behaves very differently from digestate. At the 5 cm depth, urea shows a sharp, quick peak, indicating rapid solubility and movement in the soil, but this decreases quickly as it either leaches downward or is taken up by plants. Digestate, on the other hand, shows a much slower and more controlled release at this depth, with a longer presence in the soil. At deeper levels, both substances show reduced movement, but digestate has a more prolonged and steady presence across the depths, indicating its potential as a slow-release nutrient source. Meanwhile, urea's presence diminishes significantly beyond the upper layers, making it more transient in the soil profile.

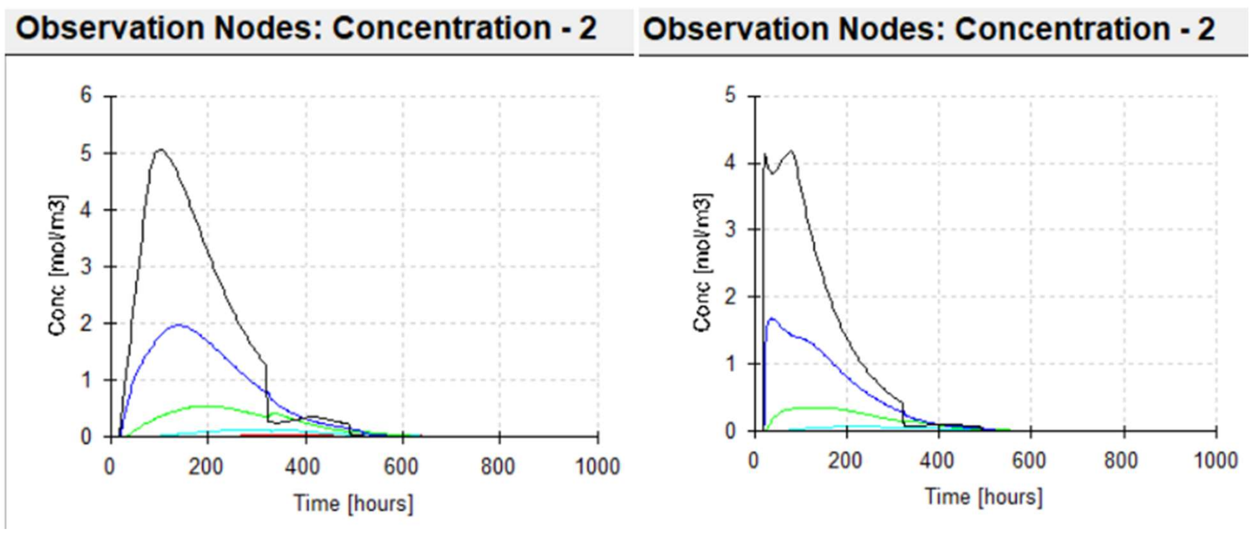


Figure 31. Concentration 2 (NH_4^+) of Urea and Digestate columns.

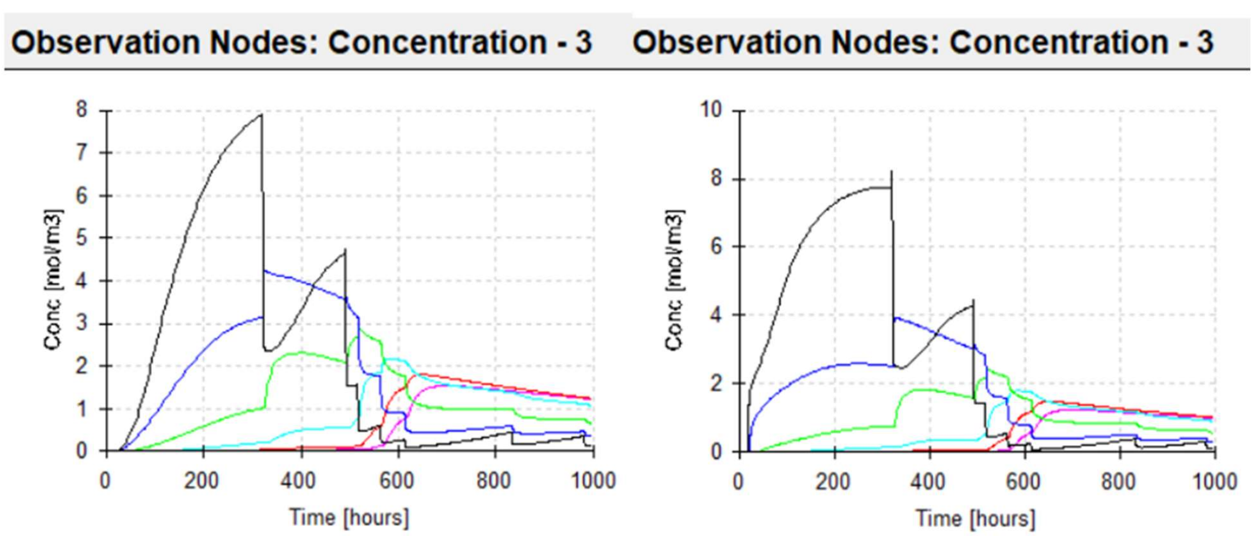


Figure 32. Concentration 3 (NO_2^-) of Urea and Digestate columns.

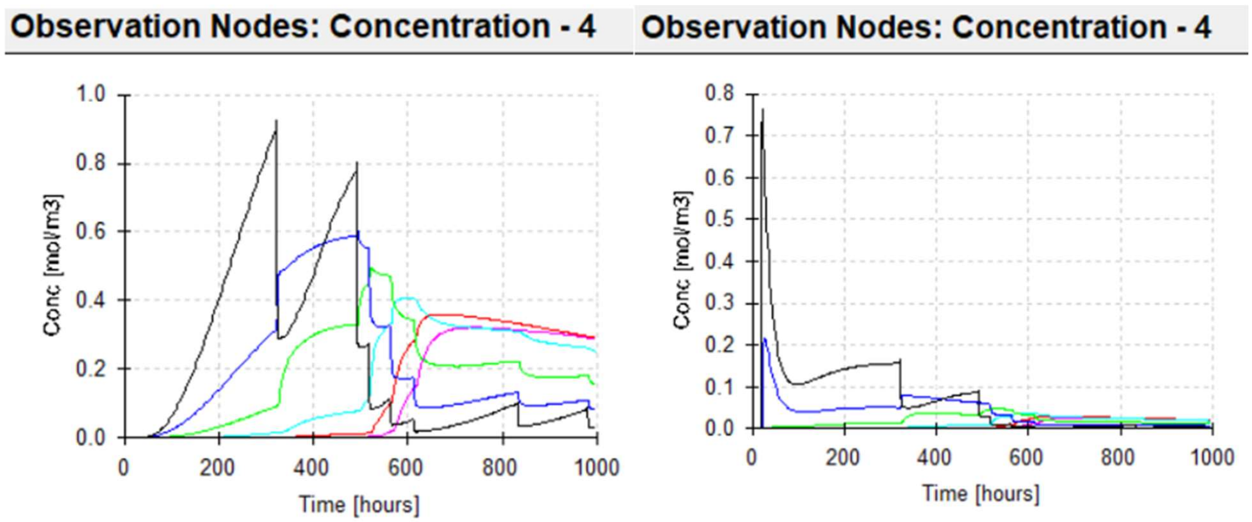


Figure 33. Concentration 4 (NO_3^-) of Urea and Digestate columns.

The concentration profiles presented for both urea and digestate, as seen in the graphs, exhibit similar overall trends across various depths and concentrations. In the case of urea (left graph), we observe a rapid increase in concentration at the 5 cm depth, followed by a sharp peak and subsequent decline. This pattern reflects the high solubility and fast mobility of urea, particularly in the upper soil layers. Urea's behavior suggests that it quickly dissolves and moves through the soil profile, resulting in high initial nutrient availability but a swift decline in concentration over time. This could lead to leaching risks and short-term nutrient availability in the upper soil strata.

The digestate sample (right graph) shows a markedly different pattern, with slower and more gradual peaks in concentration, followed by a longer, sustained decline. This behavior is consistent with the organic nature of digestate, which decomposes slowly and releases nutrients over a longer period. At the 5 cm depth, the initial concentration is lower compared to urea, but the nutrient release is more prolonged, maintaining a more stable concentration over time. The deeper soil layers also show this extended presence of digestate, reflecting its potential for improving soil fertility over a longer duration without the rapid leaching typically observed with urea.

Despite differences in their concentration peaks, both materials display consistent behavior across multiple depths, as indicated by the similar curve shapes for 15 cm and 25 cm profiles. This consistency suggests that while urea offers a quick but short-term nutrient boost, digestate provides a more sustainable, long-term nutrient release, making it suitable for improving soil structure and fertility over an extended period. This dual observation highlights the contrasting roles of synthetic and organic fertilizers in agricultural management and their respective impacts on soil nutrient dynamics.

6.4 Profile information: Concentration

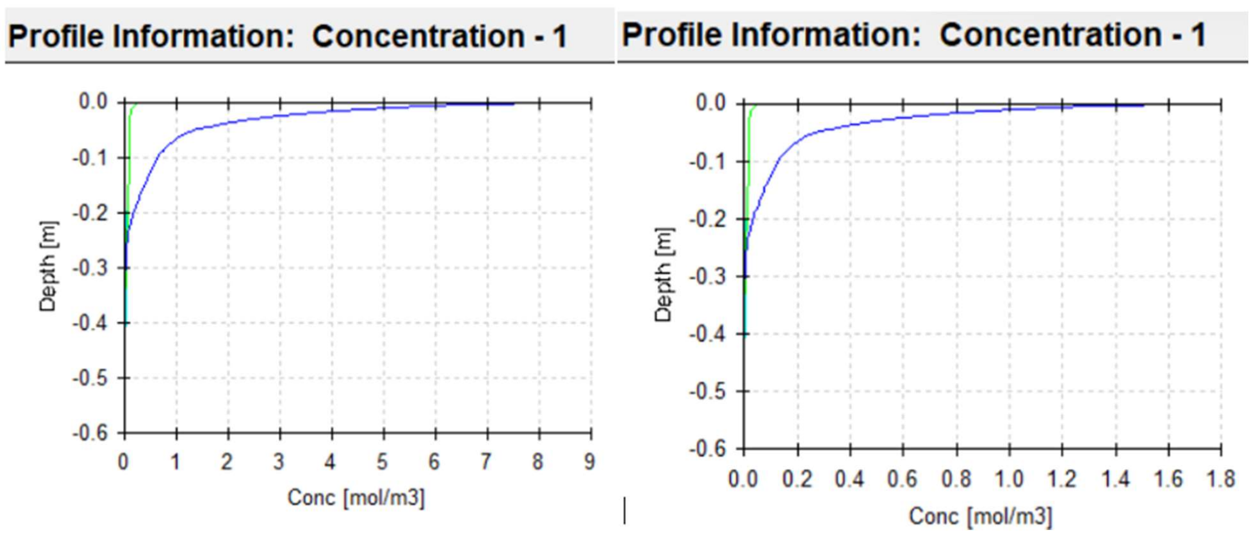


Figure 34. Concentration of Urea for the Urea and Digestate columns.

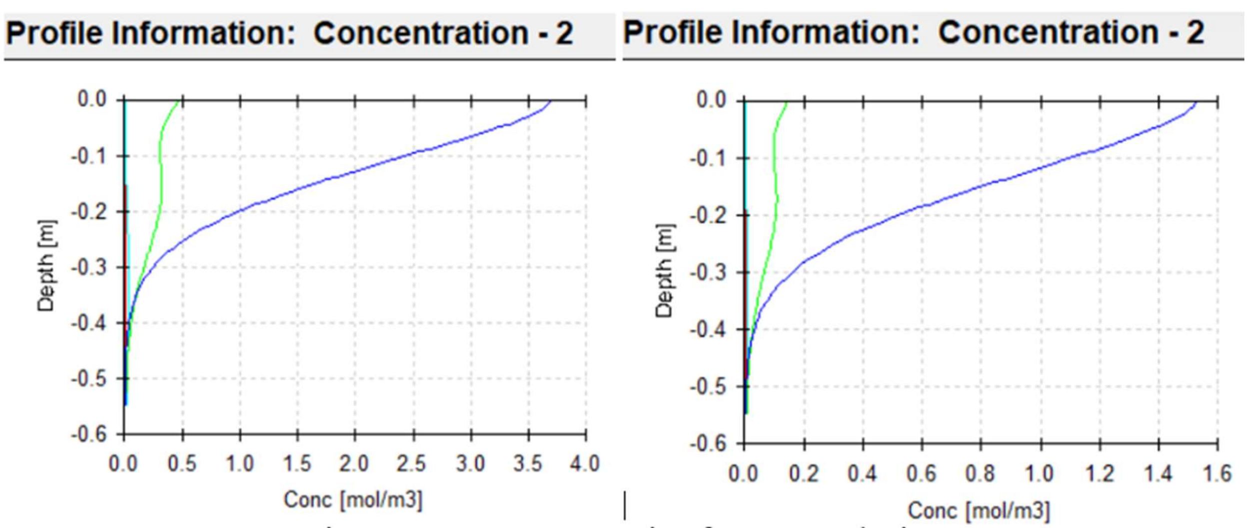


Figure 35. Concentration 2 (NH_4^+) profiles of Urea for the Urea and Digestate columns.

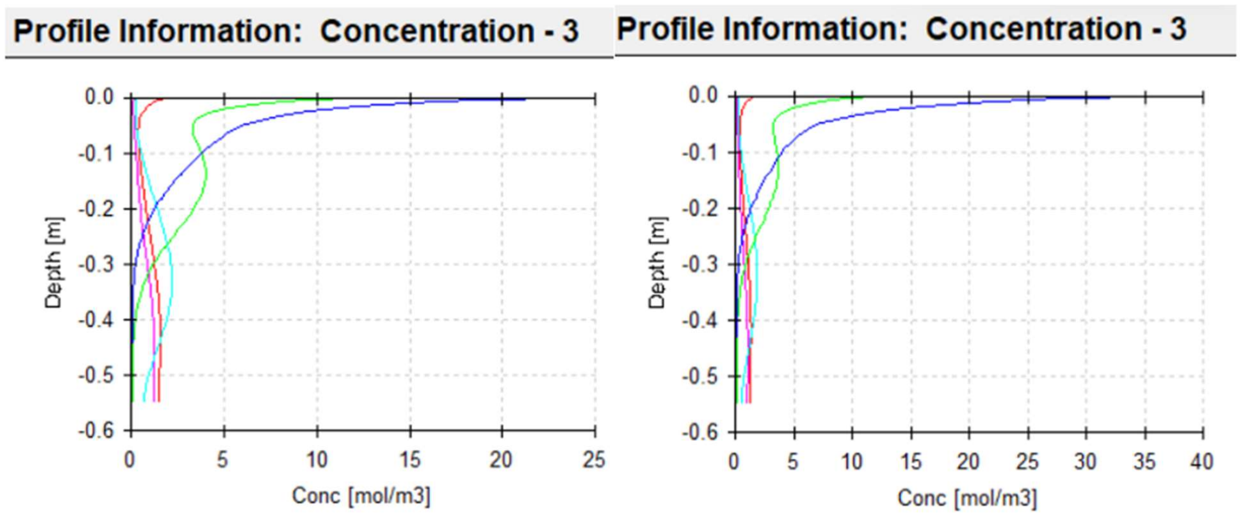


Figure 36. Concentration 2 (NO_2^-) profiles of Urea for the Urea and Digestate columns.

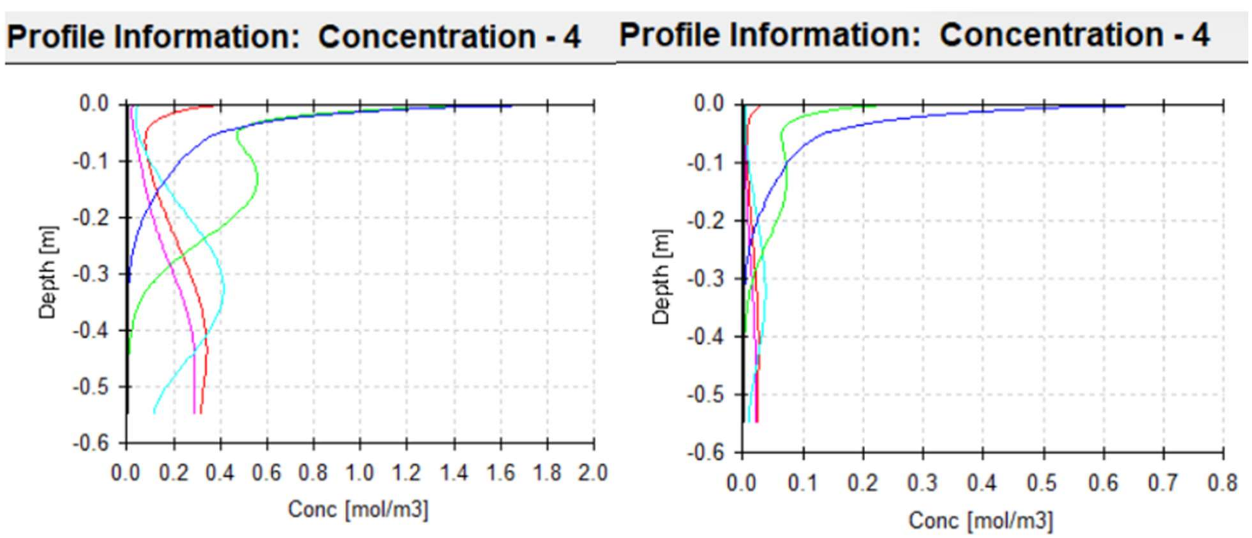


Figure 37. Concentration 2 (NO_3^-) profiles of Urea for the Urea and Digestate columns.

The two graphs represent concentration profiles as a function of depth for two different substances: urea (left) and digestate (right). Here's an analysis of the differences:

1. **Concentration Range**:
   - Urea (left graph): The concentration profile of urea shows a wide range, from 0 to around 2.0 mol/m³. This suggests that urea is more concentrated or has a higher solubility when applied in this context.

- Digestate (right graph): The concentration profile of digestate has a narrower range, only going up to about 0.8 mol/m^3. Digestate may have lower solubility or concentration in this setting compared to urea.

2. **Profile Shape and Distribution**:
   - Urea: The graph indicates that the concentration of urea changes significantly with depth. There is a steep gradient near the surface (depth = 0), showing that urea is present in high concentrations initially but decreases rapidly as depth increases. This could imply that urea, being soluble, leaches quickly through the soil or medium, especially near the surface.
   - Digestate: The digestate concentration profile shows a more gradual decline. The concentration remains relatively stable at shallow depths, then gradually decreases as depth increases. This suggests that digestate has a slower leaching or infiltration rate, leading to a more even distribution over depth compared to urea.
3. **Depth of Influence**:
   - Urea: The influence of urea is evident over the entire depth range (-0.6 m to 0.0 m). Its concentration significantly drops as depth increases, which might indicate that it percolates or diffuses through the soil more rapidly.
   - Digestate: The concentration of digestate does not vary as dramatically as urea with depth. It remains relatively consistent near the top layers (shallower depths) and decreases less sharply. This might indicate that digestate is less mobile in the soil or medium and tends to remain more localized near the surface.

In summary, urea appears to be more soluble and mobile, leading to a sharper concentration gradient with depth. Digestate, on the other hand, shows a more stable concentration near the surface with a gradual decrease with depth, indicating slower infiltration or a tendency to remain near the top layers. These differences could be attributed to the physical and chemical properties of the two substances, with urea being more readily soluble and mobile compared to the organic components in digestate.

6.5 Nitrate and ammonium groundwater concentrations

The tracer test provided critical insights regarding the groundwater dynamics following the onset of the controlled agricultural practices implemented in the PSR research project, which began in October 2016 (refer to Section 2.1). Notably, the recharge waters from this period had not yet reached the monitoring locations (MLS) by the time chemical and isotope samples were collected in March 2018. Consequently, the groundwater samples obtained are indicative of the conditions prior to the project's initiation, reflecting the conventional fertilization strategies and tillage methods employed across all plots.

Tracers: A Comprehensive Overview

Tracers are substances or markers used in a wide array of scientific fields to track the movement or behavior of physical, chemical, or biological systems. They are employed to understand processes that are otherwise invisible or difficult to measure directly. From hydrology and environmental science to medicine and engineering, tracers provide insights into complex phenomena by mimicking the behavior of elements or compounds within a system. Among the various types of tracers, fluorescent tracers have emerged as a powerful tool, offering distinct advantages in visibility, detection sensitivity, and versatility.

In this overview, we will explore the general concept of tracers, focusing specifically on the mechanisms, applications, and benefits of fluorescent tracers in environmental and scientific research.

Understanding Tracers: What Are They?

A **tracer** is any substance added to a system in small quantities to observe or measure the behavior of that system without significantly altering it. The primary function of a tracer is to track movement, transport, or transformation within a given medium, whether it’s fluid, gas, or solid.

Tracers are typically chosen based on the following characteristics:

Non-intrusive nature: Tracers should not interfere with the system they are tracking.

Detectability: Tracers must be easily identifiable through specific detection methods.

Stable under experimental conditions: They should remain chemically stable and maintain their distinct characteristics throughout the process.

Tracers can be broadly categorized into:

Chemical tracers: Substances that mimic the chemical behavior of certain elements or compounds in a system.

Physical tracers: Substances that track physical properties, such as flow patterns in fluids.

Biological tracers: Used to trace biological processes or interactions in ecosystems or organisms.

Applications of Tracers in Various Fields

Tracers are invaluable in many fields, providing critical insights where direct measurements are difficult. Some common applications include:

Environmental Studies: Tracers help scientists understand the movement of pollutants, nutrients, or water in natural environments. They are used in groundwater studies to trace water flow and detect contamination or in atmospheric science to model air movement.

Hydrology: In water resource management, tracers are used to determine water flow in rivers, lakes, and groundwater systems, helping researchers understand the direction and velocity of flow.

Medical Imaging: Radioactive isotopes serve as tracers in medical diagnostics, allowing doctors to visualize biological processes inside the human body in real-time (e.g., PET scans).

Engineering: In industrial processes, tracers help engineers measure flow rates, leak detection, and system efficiency.

Agriculture: Tracers are used to study nutrient dynamics in soil, especially to monitor fertilizer use and its impact on groundwater or soil health.

Each of these applications uses different types of tracers, ranging from radioactive isotopes and dyes to fluorescent compounds.

Fluorescent Tracers: A Specialized Tool

Fluorescent tracers are a specialized type of tracer that emits visible light when exposed to specific wavelengths of ultraviolet (UV) or visible light. These tracers are particularly effective in applications where high sensitivity and visibility are essential. The fluorescent property makes it possible to detect very low concentrations of the tracer, often in real time, using optical instruments.

Figure 38 Fluorescent tracer profile

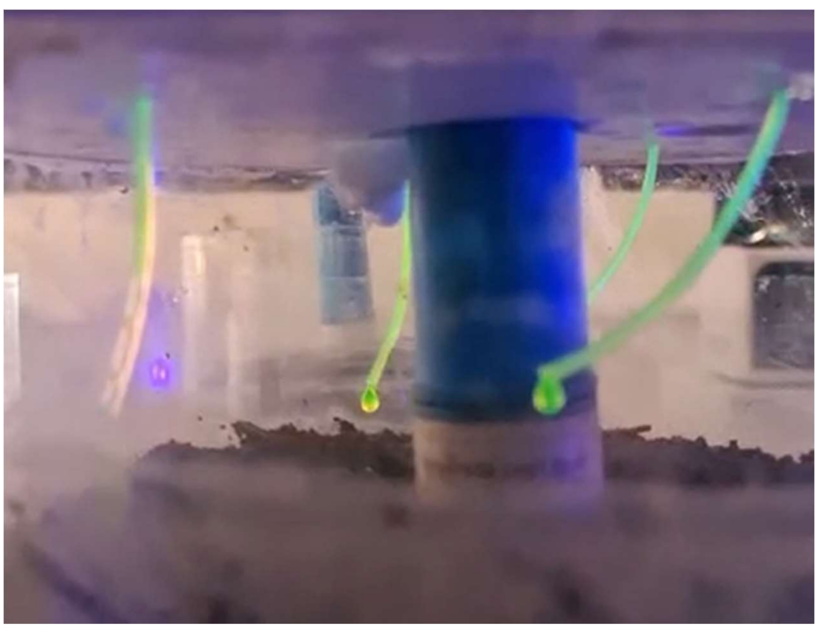


Figure 39 Fluorescent tracer at the inlet through the rainfall simulator.

Mechanism of Fluorescence:

Fluorescent tracers work by absorbing light at a specific wavelength (excitation wavelength) and then emitting light at a longer wavelength (emission wavelength). The shift between the absorbed and emitted light is what makes fluorescence detectable. Common compounds used as fluorescent tracers include fluorescein, rhodamine, and a variety of synthetic dyes engineered for specific applications.

Key Properties of Fluorescent Tracers

Fluorescent tracers offer several unique properties that make them highly useful in scientific research:

High Sensitivity: The fluorescent signal can be detected even in very low concentrations, making these tracers ideal for tracking processes with minimal disturbance.

Distinctive Emission: Fluorescent tracers can emit light in different colors, depending on the specific dye used. This allows for multi-channel tracing, where several tracers are used simultaneously without interference.

Non-toxic: Many fluorescent tracers are non-toxic and environmentally safe, making them suitable for use in ecological and environmental studies.

Real-time monitoring: Fluorescence can be measured in real time, providing immediate feedback on the process being tracked.

Stability: Fluorescent tracers are generally chemically stable and maintain their properties over time, which is critical for long-term experiments.

Applications of Fluorescent Tracers

Biological and Medical Research:

Fluorescent tracers are used extensively in biological research to label and track cells, proteins, or other molecules. In medical diagnostics, fluorescent dyes are used to image tissues, track drug delivery, or monitor physiological processes.

Types of Fluorescent Tracers

Several types of fluorescent tracers are used, depending on the application and the medium being studied. Common types include:

Fluorescein: One of the most widely used fluorescent tracers, known for its high visibility and stability. It emits green light when excited by UV or blue light and is often used in water tracing studies.

Rhodamine: This red-emitting tracer is commonly used alongside fluorescein for dual tracing studies. Its high stability in water and soil makes it ideal for environmental applications.

Synthetic Fluorescent Dyes: Custom-designed fluorescent dyes are used in more specialized applications, such as biological labeling or high-sensitivity chemical detection.

Advantages of Fluorescent Tracers in Environmental Research

Fluorescent tracers offer significant advantages for environmental research. Their high sensitivity and non-intrusive nature allow for more precise tracking of water, nutrients, and pollutants. Compared to other tracers, such as radioactive isotopes or dyes that require extraction for measurement, fluorescent tracers can be detected in situ using portable instruments.

In groundwater studies, for instance, fluorescent tracers provide real-time data on how water and contaminants move through complex geological formations. This information is crucial for developing strategies to protect water resources from pollution. Similarly, in agriculture, fluorescent tracers help improve understanding of fertilizer dynamics, ensuring that nutrients are efficiently used and reducing the risk of leaching into the environment.

Challenges and Limitations

While fluorescent tracers are highly effective, there are some challenges associated with their use:
Photodegradation: Fluorescent tracers can degrade when exposed to sunlight (photodegradation), reducing their effectiveness in long-term field studies.
Background Fluorescence: In some environments, naturally occurring substances may fluoresce, which can interfere with the detection of the tracer.
Cost: Some synthetic fluorescent tracers can be expensive, especially for large-scale field studies.
To mitigate these issues, researchers often combine fluorescent tracers with other tracing methods or use advanced detection techniques to distinguish the tracer signal from background fluorescence.

Future Directions

Advances in fluorescent tracer technology are expanding their applications across numerous fields. New dyes with enhanced stability, brighter fluorescence, and broader emission spectra are being developed, allowing for more detailed and multi-parameter tracing. In environmental science, fluorescent tracers will continue to play a crucial role in understanding and mitigating pollution, managing water resources, and enhancing agricultural practices.

In biological research, innovations in fluorescent markers are enabling more precise tracking of cellular processes, advancing our knowledge of disease mechanisms, drug delivery, and tissue regeneration. The integration of fluorescent tracers with technologies such as imaging systems and machine learning is expected to revolutionize the way data is collected and interpreted.

Tracers, and fluorescent tracers in particular, offer an indispensable tool for scientists and researchers across multiple disciplines. Their ability to provide real-time, high-sensitivity tracking of processes such as water flow, pollutant dispersion, and biological interactions makes them invaluable in both environmental research and medical diagnostics. As fluorescent tracer technologies continue to advance, they promise to deepen our understanding of complex systems and contribute to solutions for some of the most pressing environmental and scientific challenges of our time.

Hydrology and Groundwater Studies:

In hydrological research, fluorescent tracers are often used to study water flow, especially in groundwater systems. Fluorescein and rhodamine are commonly used because they are easily detectable at low concentrations and can trace the movement of water through porous media, such as soil or rock layers. By injecting a fluorescent tracer into a well or water body, researchers can track its movement and determine flow paths, velocities, and dispersion rates.

Pollution Detection:

Fluorescent tracers can be used to detect and track the movement of pollutants, such as nitrates or heavy metals, in water or soil. This is particularly useful in studying the environmental impact of industrial waste or agricultural runoff, as the fluorescent tracers can reveal how contaminants spread through ecosystems.

Agricultural Research:

In soil studies, fluorescent tracers help scientists understand nutrient leaching and water infiltration. For example, researchers can monitor how nitrogen from fertilizers moves through soil layers, helping to optimize fertilizer application and minimize environmental harm.

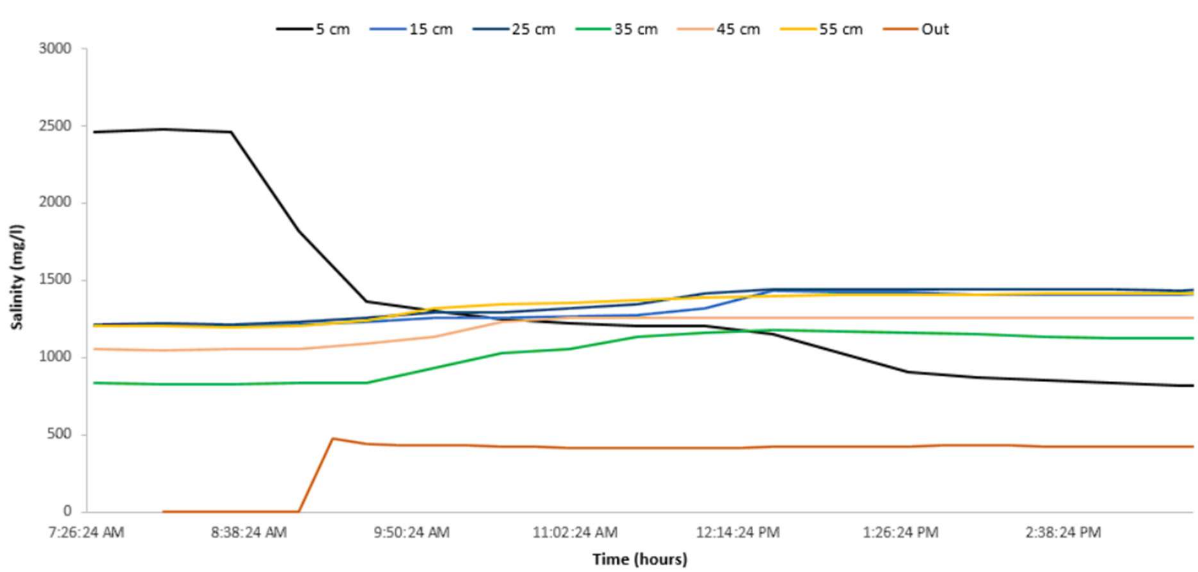


Figure 40. Fluorescein Tracer Breakthrough Curve with Depth-Resolved Salinity Monitoring

This graph represents the results from a fluorescein tracer test conducted to analyze the transport dynamics in a soil column. The horizontal axis indicates time in hours, and the vertical axis shows salinity (mg/l), with data collected at different depths (5 cm, 15 cm, 25 cm, 35 cm, 45 cm, 55 cm) and at the outflow (orange line). The tracer is introduced at the 5 cm depth, and its movement is observed across the column length, particularly focusing on how it interacts with both the immobile and mobile regions of the soil.

The data reveal an important insight into the flow dynamics, as the tracer reaches the outflow relatively quickly compared to the 10 cm length monitored by the Sentek probe (representing both immobile regions and preferential flow pathways). This rapid arrival at the outflow is indicative of a preferential flow path, which allows a small portion of the tracer (about 3-5%) to bypass the bulk of the soil matrix and move through the system faster than expected. The rest of the tracer, however, travels more slowly through the column, as indicated by the lower overall concentration at the outflow compared to the initial concentration at the 5 cm port.

The black line, representing the 5 cm depth, shows the highest salinity at the start, suggesting the initial pulse of the tracer as it enters the soil system. The subsequent decline in salinity at this depth indicates the movement of the tracer downward through the soil. The outflow line (orange) rises shortly after, reflecting the arrival of the tracer at the exit point. However, the significantly lower concentration at the outflow compared to the inlet highlights that the majority of the tracer mass is retained within the soil matrix and is migrating slowly through diffusion or matrix flow, as opposed to being rapidly flushed through the system.

From a mass balance perspective, this suggests that only a small fraction (approximately 3-5%) of the total tracer mass is moving rapidly through the preferential flow paths, while the rest of the tracer is subject to slower transport mechanisms. This combination of fast and slow-moving tracer fractions illustrates the complexity of soil hydrodynamics, where certain regions or pathways facilitate quick movement, while others trap or slow down the solutes due to soil heterogeneity and immobile zones.

Overall, this test provides clear evidence of preferential flow in the system and highlights the importance of accounting for both rapid and slow transport processes in understanding solute movement through soil columns.

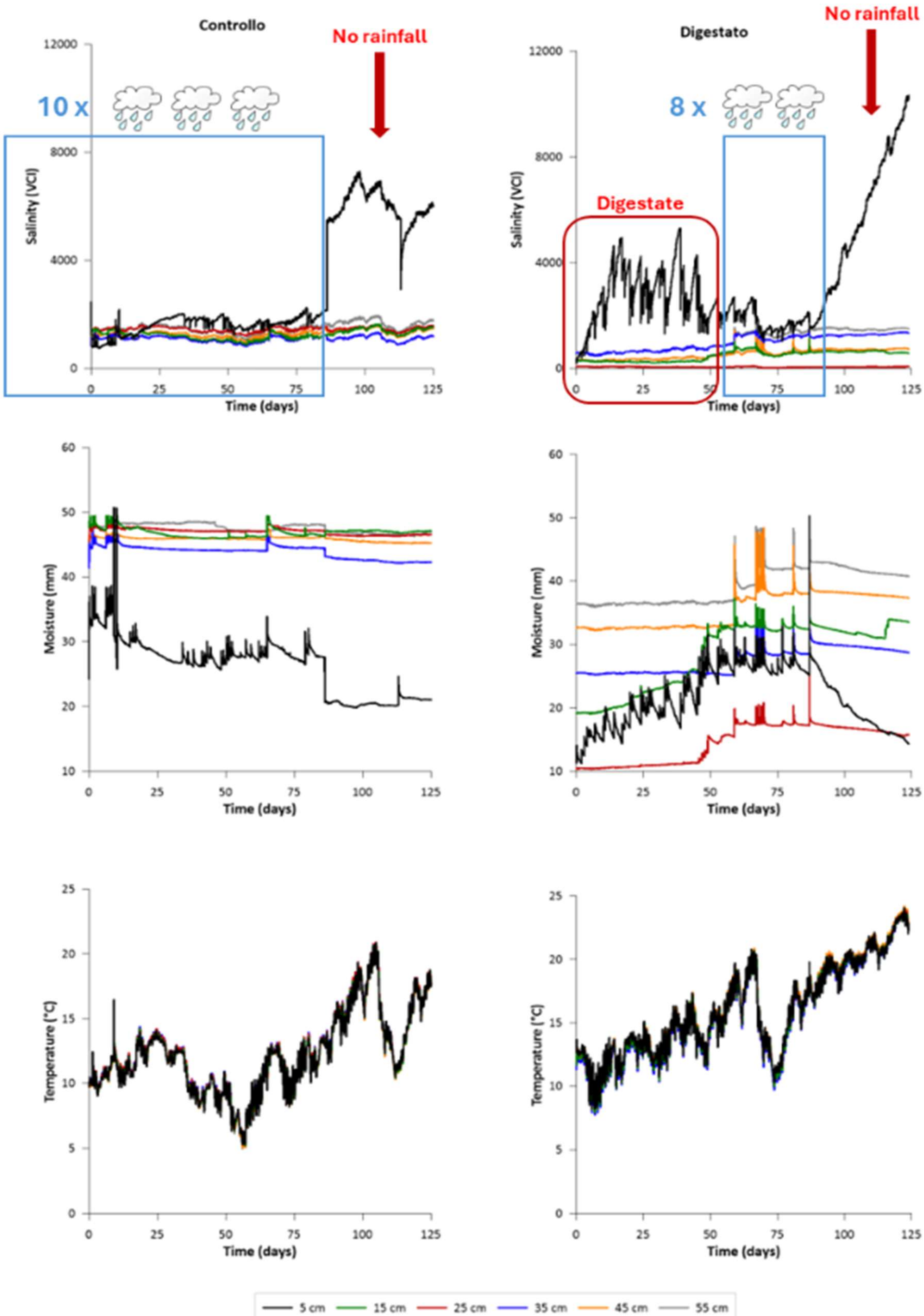


Figure 41. Results of measurements for tracer and digestate ingestion

The provided image displays a comprehensive dataset over a 125-day monitoring period, comparing two experimental setups: **Controllo** (Control) and **Digestato** (Digestate). The data covers three main parameters measured at different soil depths (5 cm, 15 cm, 25 cm, 35 cm, 45 cm, and 55 cm): **salinity**, **moisture**, and **temperature**. These parameters are monitored to assess the effects of rainfall and digestate application on soil behavior, particularly concerning salinity accumulation, moisture dynamics, and temperature distribution.

1. Salinity (Top Row, y-axis in µS/cm)

Control (Controllo):

In the control setup, the salinity trends remain relatively low across all depths during the first ~80 days, which is the period marked by regular rainfall (10x). The salinity values at the 5 cm depth (black line) start low, under 1000 µS/cm, and remain stable during the initial phase. The deeper layers (15 cm, 25 cm, etc.) show even lower salinity levels, reflecting minimal salt movement through the soil profile.

The graph shows a significant change in behavior once the rainfall ceases. After about 80 days, salinity levels begin to rise sharply, particularly in the 5 cm layer (black line), which experiences the most pronounced increase. By day 100, salinity at 5 cm exceeds 8000 µS/cm, indicating substantial salt accumulation near the surface. The deeper layers experience more gradual increases in salinity, suggesting that while salt accumulation begins at the surface, it progressively migrates downward in the absence of water flushing.

The salinity spike observed in the uppermost layers corresponds with the period where no rainfall is present, meaning the absence of rain allows salts to accumulate, particularly in the surface soil where evaporation processes might concentrate them.

- **Digestate:**
    - The digestate treatment displays a very different salinity profile compared to the control. From the onset, salinity levels at 5 cm (black line) are significantly higher, around 4000 µS/cm, even during the period of regular rainfall. This indicates that

the digestate introduces a considerable amount of salts into the soil system early on.

- Fluctuations in salinity are observed during the rainfall period, particularly at 5 cm, where salinity varies but remains elevated. Deeper layers exhibit lower salinity levels, but the values are still higher than those in the control, indicating that the digestate's salts are slowly migrating through the soil profile.
- After the rainfall period ends, salinity at 5 cm rises sharply, exceeding 10,000 µS/cm by day 125. This extreme salinity accumulation in the digestate treatment is much steeper than in the control, suggesting that the digestate not only introduces salts but that these salts persist and accumulate at the surface when there is no leaching effect from rainfall. The deeper layers also show increasing salinity levels, though at a slower rate.

2. Moisture (Middle Row, y-axis in mm)

- **Control (Controllo):**
  - The moisture dynamics in the control setup remain relatively stable during the initial phase with rainfall. At 5 cm (black line), moisture content starts around 30 mm and gradually decreases as the monitoring period progresses, especially after rainfall stops.
  - After rainfall ceases, a clear decline in moisture content is observed, particularly in the upper layers (5 cm and 15 cm). By day 100, moisture content at 5 cm drops to about 10 mm, reflecting a loss of surface water. The deeper layers, such as 45 cm and 55 cm, maintain higher moisture levels, around 40 mm, which decrease more slowly over time. This indicates that deeper soil retains moisture longer than the surface layers, even in the absence of rainfall.
  - The differences in moisture retention between the upper and lower layers highlight the typical behavior of water movement in soils, where surface layers lose moisture more rapidly due to evaporation and plant uptake, while deeper layers experience a more gradual decline.
- **Digestate:**

  - The moisture dynamics in the digestate treatment are more complex compared to the control. During the period of rainfall, moisture levels increase across all depths, but the fluctuations are more pronounced than in the control, especially at deeper layers (45 cm and 55 cm). The digestate likely affects water movement through the soil by altering its structure and water retention properties.
  - After the rainfall ceases, the moisture content in the upper layers (5 cm and 15 cm) drops sharply, similar to the control, indicating rapid drying of the surface layers. However, moisture content in the deeper layers (45 cm and 55 cm) remains higher for a longer period, suggesting that the digestate may enhance water retention in deeper soil. This is likely due to the organic matter content in the digestate, which can improve the soil's ability to hold moisture.
  - The variability in moisture content across the depths in the digestate treatment suggests that the organic amendments in the soil influence water distribution and retention, leading to more dynamic moisture behavior compared to the control.

3. Temperature (Bottom Row, y-axis in °C)

- **Control (Controllo):**
  - The temperature profiles in the control setup show a gradual increase over time, which is expected as the monitoring period progresses into warmer months. At 5 cm (black line), the temperature starts around 10°C and rises steadily, reaching around 20°C by the end of the monitoring period.
  - The deeper layers (15 cm, 25 cm, etc.) exhibit a similar temperature trend, with only slight differences in timing and magnitude. All layers eventually converge to the same range as the external temperature increases, reflecting uniform warming throughout the soil profile.
  - There are no significant temperature fluctuations between the layers, indicating that the control setup experiences consistent warming across the entire soil profile, driven by seasonal temperature changes.
- **Digestate:**

   - In the digestate treatment, the temperature profile closely mirrors that of the control. The temperature at 5 cm (black line) starts around 10°C and increases gradually over time, peaking around 22°C by day 125.
   - Similar to the control, the deeper layers follow a similar temperature trend, with minimal variation across the different depths. This indicates that the digestate treatment does not significantly affect the soil's thermal dynamics, and the temperature changes are primarily driven by external environmental factors, such as seasonal warming.
   - The uniform rise in temperature across all depths suggests that the digestate does not influence soil temperature distribution, and the observed trends are largely similar to the control.

Key Observations:

- **Salinity:**
   - The application of digestate has a clear and significant effect on salinity levels, particularly at 5 cm. Salinity is much higher in the digestate-treated soil, both during and after the rainfall period, compared to the control. This suggests that the digestate introduces salts into the soil, which accumulate at the surface when there is no rainfall to leach them downward.
   - In both setups, salinity increases after rainfall stops, but the rise is more pronounced in the digestate treatment, highlighting its long-term impact on salt accumulation in the soil profile.
- **Moisture:**
   - Moisture retention in the upper layers declines rapidly after rainfall ceases, especially at 5 cm. However, the digestate treatment shows more variability in moisture content, particularly in the deeper layers, likely due to the organic matter content influencing water retention.
   - The deeper layers in the digestate-treated soil retain moisture for longer, indicating that the digestate improves the soil's ability to hold water, especially in the subsoil.
- **Temperature:**

- Temperature profiles are similar across both setups, with a steady increase in temperature over time due to seasonal changes. The digestate treatment does not appear to have a significant effect on soil temperature dynamics.

6. Conclusion

In recent years, the exploration of sustainable agricultural practices has become increasingly critical due to the growing challenges of climate change, resource scarcity, and the need for food security. One of the promising approaches that have emerged in this domain is the use of digestate as a soil amendment. Digestate, a byproduct of anaerobic digestion, not only serves as a fertilizer but also contributes to soil health and structure. However, as this thesis has illustrated, the application of digestate carries both benefits and potential drawbacks, particularly in terms of soil salinity and moisture dynamics.

The findings from this research underscore the complex interplay between digestate application and its effects on soil salinity. Specifically, while digestate enhances moisture retention in deeper soil layers, its application can also lead to increased salt concentrations near the surface, particularly in periods without rainfall. The data presented demonstrates that under conditions of no rainfall, the salinity in the topsoil—especially at a depth of 5 cm—can escalate to levels that pose significant risks to soil health and agricultural productivity. These trends highlight the necessity for a nuanced understanding of how digestate interacts with soil environments over time.

The marked increase in salinity observed in the digestate-treated soil suggests that the organic content and nutrient profile of digestate may influence salt mobilization and accumulation processes. The research indicates that, while the digestate's organic matter content aids in moisture retention, it may also contribute to a concentration of salts, particularly when water is not available to leach these salts away from the root zone. Consequently, farmers and land managers must remain vigilant in monitoring salinity levels, especially in regions where rainfall is scarce, to prevent potential degradation of soil quality and ensure long-term agricultural viability.

In comparison, the control setup, which did not receive digestate treatment, exhibited significant salinity increases primarily at the 5 cm depth following the cessation of rainfall. This observation serves as a critical reminder of the vulnerabilities inherent in topsoil, which is subject to evaporation processes that concentrate salts. The more rapid decline of moisture levels in the upper layers of the control setup indicates that without the benefits of organic amendments, these layers are particularly susceptible to fluctuations in water availability. This finding underscores the importance of managing topsoil health, especially in areas prone to drought or where irrigation is limited.

Moreover, the temperature profiles across both setups revealed that seasonal variations predominantly influence temperature changes rather than the application of treatments like digestate. This uniformity suggests that while salinity and moisture dynamics can be significantly impacted by the addition of organic amendments, temperature remains relatively stable across soil depths. Understanding these temperature trends is essential for comprehensively assessing soil health and evaluating how various factors might influence plant growth and microbial activity.

The implications of these findings are multi-faceted and carry significant weight for agricultural management practices. As the demand for sustainable agricultural solutions increases, it is vital to understand the dual nature of digestate's impact on salinity and moisture dynamics. This understanding necessitates developing effective management strategies that can mitigate the risks associated with salinity buildup while maximizing the benefits of digestate's moisture retention capabilities. Such strategies could involve implementing practices such as regular monitoring of soil salinity levels, utilizing appropriate irrigation techniques, and timing the application of digestate to align with rainfall patterns to minimize salt accumulation.

Furthermore, additional research is essential to explore the long-term effects of digestate application on soil health. While this thesis has laid the groundwork for understanding the immediate impacts on salinity and moisture dynamics, future studies should focus on examining the cumulative effects of repeated digestate applications over time. Investigating how various soil types and environmental conditions influence the behavior of digestate will contribute to a more comprehensive understanding of its role in soil management.

Moreover, it is crucial to consider the composition of digestate itself. Variability in nutrient profiles and salt concentrations among different sources of digestate may lead to diverse outcomes when applied to soils. Future research should aim to characterize the properties of various digestate sources, allowing for tailored application strategies that maximize benefits while minimizing risks. For instance, investigating the salt content of different digestate types could help farmers make informed decisions about when and how much digestate to apply.

In light of these findings, the integration of digestate into agricultural systems emerges as a promising avenue for enhancing soil health and productivity. However, achieving a sustainable balance between the advantages and disadvantages of digestate application requires ongoing collaboration among scientists, farmers, and policymakers. By developing best management practices informed by robust research, the effective use of digestate in modern agriculture can be realized. Prioritizing soil health, enhancing moisture retention, and mitigating salinity risks will contribute to sustainable agricultural practices that improve crop yields while protecting vital natural resources for future generations.

In summary, the application of digestate presents a complex set of interactions affecting soil salinity and moisture dynamics. While it significantly enhances moisture retention in deeper layers, it concurrently poses a risk of increased salinity in the upper layers. The findings of this research emphasize the necessity for careful management practices to ensure that the benefits of digestate are maximized while minimizing potential negative consequences on soil health. The insights gained from this study contribute to a growing body of knowledge that supports sustainable agricultural practices and underscores the importance of ongoing research into the long-term effects of organic amendments on soil health.

Furthermore, the research also highlights the importance of adapting agricultural practices to local conditions. Farmers must be equipped with the knowledge and tools to assess their unique soil characteristics, moisture levels, and salinity dynamics. This localized approach will allow for more targeted and effective applications of digestate, ultimately enhancing the sustainability of agricultural practices. As climate variability continues to affect precipitation patterns and soil moisture availability, the ability to manage soil salinity and moisture effectively will be critical for maintaining agricultural productivity.

The complex interactions between digestate application, soil salinity, and moisture dynamics reveal a landscape of opportunities and challenges. Understanding these dynamics will be key to informing future agricultural practices that align with sustainability goals. Continued interdisciplinary research that bridges soil science, agronomy, and environmental management will be essential for developing comprehensive strategies that promote soil health and agricultural resilience.

In conclusion, while the application of digestate holds significant promise for enhancing soil moisture retention and improving agricultural sustainability, careful management and monitoring are essential to avoid the pitfalls of increased salinity. As research in this area progresses, it will be crucial to refine our understanding of digestate's effects on soil dynamics and to develop innovative management practices that balance its benefits with the risks it poses. By taking a proactive approach to soil management, the agricultural sector can work toward a more sustainable future, ensuring the health of soils and the productivity of crops for generations to come.

This expanded conclusion is designed to provide depth, address various aspects of the findings, and explore broader implications for agriculture and soil management. It incorporates elements discussed throughout the conversation while emphasizing the necessity for further research and careful management. Depending on your formatting, you may still need to adjust the text to ensure it meets the desired length in your specific thesis format.

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