The influence of envelope material on sedimentation and water quality in subsurface drainage

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The influence of envelope material on sedimentation and water quality in subsurface drainage

Dräneringsfiltrets påverkan på sedimentation och vattenkvalitet vid täckdikning

Linnea Berggren Sjögård

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Abstract

A well-functioning drainage system is an essential component of crop production. With climate change bringing increased precipitation, higher demands are placed on our drainage systems. Throughout the past decades, little research has been conducted on drainage materials, and our most common drain envelope, gravel, has become expensive. However, new materials are now available. These new materials must be examined to improve the functionality of our drainage systems in agriculture. The overall aim has been to use measured data in a field trial to investigate how various drainage envelope materials in clay soils affect subsurface drainage, sediment accumulation, subsurface runoff, turbidity and nitrogen and phosphorus concentrations. Furthermore, it sought to provide insight into whether using an envelope can help to reduce sediment accumulation and nutrient leaching compared to drainage pipes without an envelope. The field trial, performed in central Sweden during the hydrological years 2023-2025, examined treatments with no envelope, synthetic envelope and crushed rock envelope. During an excavation, 40 cm of the pipe was dug up. In general, a small amount of sediment was found in all pipes. Most sediment was found in the treatment without an envelope (5.94 g per 40 cm pipe), while the synthetic envelope had the significantly lowest amount (0.89 g). Pipes with crushed rock envelopes had the largest number of particles in the size range of 0.06-0.2 mm (21.3%), which pose the highest risk of clogging the pipes. The results showed that the use of an envelope decreases the sediment accumulation ($p = 0.0009$) and the concentration of nitrogen ($p < 0.02$). In the first hydrological year, the average nitrogen concentration was reduced from 10.91 mg/l (no envelope) to 7.86 mg/l (synthetic envelope). The result for phosphorus concentrations was not significant. The findings showed no effect on turbidity when using an envelope. To verify these results, a follow-up study examining sedimentation in the pipes and nitrogen and phosphorus concentrations after about a decade is recommended to determine if the long-term results of sediment accumulation and nutrient concentrations in the pipes are consistent. Further research should also explore whether nitrogen and phosphorus concentrations decrease with the use of an envelope on soils other than clay. The decrease of nutrient concentrations with an envelope is positive for the future climate with increases in precipitation. The use of an envelope could therefore be a strategy to reduce nitrogen leaching in drainage, but more research is needed to confirm these findings.

Keywords: envelope, filter, drainage, nutrient leakage, turbidity

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Abbreviations

ANOVA	Analysis of Variance
FNU	Formazin Nephelometric Unit
HSD	Honest Significant Difference
ISO	International Organization for Standardization
N	Nitrogen
P	Phosphorus
p	Probability value
PLM	Prewrapped loose material
R^2	Coefficient of determination
SMHI	Swedish Meteorological and Hydrological Institute

1. Introduction

Due to a warmer climate, precipitation has and will continue to increase, especially during winter (SMHI 2025). This can place a serious demand on drainage in agriculture and can also increase the risk of nutrient leakage from the fields (Fogelfors et al. 2009; Rashmi et al. 2017). A higher temperature also creates a longer vegetation period in Sweden. The vegetation period will start earlier and end later, with a greater elongation in spring than in autumn (SMHI 2024). In order to benefit from a longer vegetation period, a well-functioning drainage system must be in place to allow access into the field in early spring and late autumn, especially considering today's larger and heavier agricultural machines (Swedish Board of Agriculture 2010; Rydberg et al. 2019). Because of climate change, a well-functioning drainage system is a key factor for future crop production.

Drainage in agriculture is when water is led away from arable land, either in open ditches or in subsurface drainage pipes that are installed in the soil. This process is an essential prerequisite for crop production (Swedish Board of Agriculture 2010). When the water in the soil's pore system is drained, the soil is instead filled with air, which enables the plant roots to grow deeper into the soil. It allows the plants to increase their root volume, which gives the plant a larger volume of soil from which to absorb water and nutrients (Weidow 2018). The soil volume should consist of 20-25% air and 20-25% plant-available water to provide the crop with the optimal growing conditions (Swedish Board of Agriculture 2010). Drainage with even infiltration into the soil can therefore increase yields and counteract nutrient leakage of nitrogen and phosphorus (Swedish Board of Agriculture 2012; Weidow 2018). A poorly drained soil can generate problems with surface runoff and erosion, which can lead to losses of particulate phosphorus, uneven drying, poorer soil bearing capacity and a greater risk of soil compaction (Swedish Board of Agriculture 2012). The proportion of arable land that is satisfactorily drained in Sweden is 61% (Swedish Board of Agriculture 2024).

In subsurface drainage, corrugated perforated pipes are installed in the soil that are connected to a main pipe that leads the water from the field out to a recipient, such as a natural water course. Systematic drainage is when the pipes are laid out in a regular pattern over the entire area (Swedish Board of Agriculture 2018). In

Sweden, 47% of arable land is systematically drained (Swedish Board of Agriculture 2024).

In subsurface drainage, an envelope is often placed around the pipe to increase the permeability around the pipe and prevent soil particles from being drawn into the pipe through its perforations, which could otherwise risk the pipes becoming clogged and impair the drainage function (Stuyt et al. 2005).

During the 1960s, several drainage experiments were carried out, however since the 1990s, almost no drainage experiments have been conducted in Sweden (Joel & Wesström n.d.). Moreover, throughout the 1990s, much state-funded drainage research in Sweden was discontinued (Rydberg et al. 2019). This has consequently led to a knowledge gap and a lack of research on which new envelope materials perform best across different soils and over the long term (Swedish Board of Agriculture 2020)

Much of the knowledge that currently exists regarding drainage and envelope materials was produced during the 1900s with the materials and resources that were available then. Natural gravel and sawdust were the materials that were predominantly used as envelope materials in subsurface drainage. Today, natural gravel is a finite resource, and high quality sawdust that lasts for a long time is difficult to find (Swedish Board of Agriculture 2020). Thus, we must assess both the materials that we are using and new materials to determine how well they work as envelope materials. In other words, how the envelope materials affect the drainage system and the crop. According to Falk (2019), drainage systems without envelopes should be investigated to understand how necessary envelopes are, and this should also be investigated in different types of soils.

A drainage system should remain in the soil for a long period. When installing new drainage, it should be designed with a lifespan of at least 50 years (Swedish Board of Agriculture 2012). Therefore, it is important to investigate how much sediment accumulates in the pipes to determine how long the drainage will maintain its function, depending on the envelopes used. At present, gravel is commonly used as an envelope, which means that a heavy gravel cart must be taken out to the field. This is not preferable as it causes significant soil compaction. Gravel also entails a high installation cost. Not having to apply gravel as an envelope around the pipe would substantially minimise costs and reduce soil compaction in the field. Investigations into whether an envelope is necessary and what other envelope materials could be used are therefore needed to find more sustainable solutions.

1.1 Aim and question

The overall aim was to use measured data in a field trial to investigate how newly constructed drainage systems with different envelope materials and re-drainage of clay soils:

- Affect sediment deposition in the drainage pipes and thereby impact maintenance needs and the long-term sustainability of the drainage system.
- Affect runoff, turbidity and nutrient leaching of nitrogen and phosphorus.
- Provide insights into whether envelope materials contribute to reduced sediment deposition and altered nutrient leakage compared to pipes without an envelope.

1.1.1 Hypothesis

Four hypotheses were formulated about possible results:

a) There will be sediment in the pipes because the risk of sedimentation in the pipes is the greatest immediately after installation, before the soil has stabilised.
b) There will be more sediment in the pipes without an envelope, as nothing separates the pipes from the surrounding soil to prevent sediment from entering.
c) The turbidity is higher in water from pipes without an envelope due to the increased sediment load compared to other treatments.
d) The increased amount of sediment and turbidity in the pipes without an envelope leads to increased concentrations of nitrogen and phosphorus nutrients.

2. Background/Literature review

From the outset of subsurface drainage, it was recognised that a method was needed to prevent soil from entering the drainage pipes. By the early 1800s, problems with pipe clogging had already been documented. Since then, a range of materials have been used, including straw, peat, fabric, sand and gravel (Yannopoulos et al. 2020). In this section, the function of envelopes will be explained, followed by descriptions of different envelope materials and the circumstances in which they are most suitable. Soil type and site characteristics are crucial for choosing the appropriate envelope material. They also determine the maintenance needs of the drainage system. Envelopes can also influence the amount of runoff and the quality of drainage water.

2.1 Envelope materials

In Sweden today, the term filter material is often used to describe an envelope in subsurface drainage. By definition, a filter is "a porous article or mass (as of paper or sand) through which a gas or liquid is passed to separate out matter in suspension" (Merriam-Webster 2025). This means that if a filter is used as an envelope in subsurface drainage, the filter would eventually become clogged and hinder the permeability around the pipe. An envelope is not a filter, but it prevents certain sizes of soil particles from entering the pipe and does not become clogged over time (Wright & Sands 2001; Stuyt et al. 2005; Yannopoulos et al. 2020). This is why I use the term "envelope" rather than "filter" throughout this thesis.

An envelope, the material closest to the drainage pipe, generally has four criteria: (1) Create a zone with high permeability close to the pipe, (2) prevent particles that are too big to be transported out of the pipe from entering the pipe, (3) stabilise the pipe under load and (4) protect the pipe during installation of the drainage pipe (Jonsson 1985; Håkansson 1989; Dräneringscentralen rf 2001; Täckdikningsföreningen rf 2015). Yannopoulos et al. (2020) cite two reasons for using envelopes: to create permeability around the pipe and to prevent soil particles from entering the pipe and clogging it. The most important feature of an envelope is that it should have pores between the particles that are large enough for a well-functioning water flow into the pipe, and at the same time, it should have sufficiently small pores so that the pipe does not become clogged by the small and fine particles present in the surrounding soil (Ead et al. 2007).

In the beginning, after the drainage system is installed, the greatest risk of sedimentation in the pipes occurs. The risk of silting decreases over time when the soil stabilises (Taylor 1973; Jonsson 1985). There are peat soils and sandy soils that are constantly unstable and therefore always possess a risk of clogging (Jonsson 1985). Envelopes are porous materials divided into three categories: mineral materials (e.g. gravel), organic materials (e.g. sawdust) and synthetic materials (Stuyt et al. 2005; Swedish Board of Agriculture 2018).

2.1.1 Mineral envelopes

Gravel is the most secure choice for envelope material. It does not become clogged over time and has a good water conductivity (Jonsson 1985; Dräneringscentralen rf 2001). Gravel envelopes are also the most commonly used envelope material both in Sweden and worldwide (Jonsson 1985; Stuyt et al. 2005; Täckdikningsföreningen rf 2015; Swedish Board of Agriculture 2018). Another important quality is its unlimited permanence (Jonsson 1985).

However, it is vital that the gravel has an even particle distribution. It must not contain too much fine material, as this impairs water conductivity. The finest material in the gravel can be dragged into the pipes and clog them. On the other hand, too large a proportion of coarse material impairs the filtration ability of the gravel. When using crushed rock, the same requirements apply to the particle size distribution. There is little experience with crushed rock as an envelope material (Täckdikningsföreningen rf 2015), but its usage has increased in recent years. The Swedish Board of Agriculture (Sw. Jordbruksverket) (2018) recommends a gravel size of 2-8 mm for both gravel and crushed rock.

A disadvantage of gravel is that it accounts for a large share of the drainage cost (Stuyt et al. 2005; Ritzema et al. 2006). Gravel is also heavy, which contributes to increased soil compaction during drainage system installation.

2.1.2 Organic envelope

Organic envelopes used in Sweden are sawdust, coconut fibres, straw or peat (Jonsson 1985). They can be applied directly to the pipes during construction or wrapped around the pipes, as prewrapped loose material (PLM). In Scandinavia, organic envelopes have been the most successful due to lower soil temperatures, which reduce the microbiological activity and thus the degradation of the organic material (Stuyt et al. 2005). Sawdust has good filtration ability but poorer permeability than gravel. Therefore, sawdust, as is the case with gravel, must not contain too much fine material. After about 20 years in the soil, the sawdust is decomposed in half, but this of course varies with the soil type (Jonsson 1985).

Coconut fibres are wrapped around the drainage pipes. The disadvantage of coconut fibre is that it breaks down quickly, within only 2-5 years. The rapid degradation of coconut fibres has increased the demand for affordable synthetic envelopes (Stuyt et al. 2005).

2.1.3 Synthetic envelope

In recent decades, the development of synthetic prewrapped envelopes has increased in Europe and the United States (Ritzema et al. 2006). Synthetic envelopes such as PLM are most often used in Europe and usually replace gravel, which was used more in the past. Synthetic envelopes consist of various polymeric materials, some of which can be recycled. The fibres consist of polyamide (PA), polyester (PETP), polyethylene (PE) and polypropylene (PP). Today, recycled synthetic materials are often used, for example, recycled PP fibres. The pipes are wrapped with these synthetic fibres, which cover them entirely and thus make them easier to manage. The envelopes are sensitive to sunlight, but once buried, they cannot decompose. This renders them a long-lasting material that can replace gravel or organic envelopes (Stuyt et al. 2005).

Synthetic envelopes are available as PLM and geotextile. Geotextile is a thin and permeable material that is woven, non-woven or knitted. It is rarely used as an envelope because it is an expensive material, and in Europe, its fine structure is considered to increase the risk of clogging. However, in France, Canada and the United States, synthetic geotextiles, which are the most common synthetic envelopes, are used on a large scale because they are produced locally (Stuyt et al. 2005). Geotextiles as drain envelopes have also become relevant in China (Yang et al. 2023). New types of solutions for envelopes are also being developed, such as Hydroluis in Turkey, where the drainage pipe is covered from above to 2/3 by an unperforated outer pipe (Bahçeci et al. 2018).

Microplastics can be transported in the soil and reach groundwater (Wanner 2021). As they are composed of plastics, a disadvantage of synthetic envelopes is that they can leak microplastics into drainage water. Indeed, Bigalke et al. (2022) found microplastics in drainage water.

2.1.4 No envelope

No envelope refers to when the drainage pipe is placed in the soil with no extra material around it. Agar (2011) observed that in clay soils with more than 40% clay, the risk of clogging in pipes without envelopes was negligible and therefore believes that envelopes are not needed on these soils. According to Wright & Sands (2001), clay soils of 25-30% clay do not require an envelope.

2.2 Soil types

It is the properties of the soil that determine whether an envelope is needed and what type of envelope is required (Dräneringscentralen rf 2001; Stuyt et al. 2005; Agar 2011). The particle size distribution in the soil is crucial. Particles smaller than 0.02 mm are carried with the water, resulting in turbid outflow. Soil with a particle size between 0.05-0.15 mm (fine sand) is somewhat mechanically unstable and, as such, sensitive to erosion, thereby necessitating an envelope (Stuyt et al. 2005). Particles within that size range (0.05 – 0.15 mm) are also the ones that clog the drainage pipes (Jonsson 1985).

Soils with low cohesion capacity, which is the ability of the particles to stick together, are also considered unstable and thus demand an envelope (Stuyt et al. 2005). Coarse silt (0.02-0.06 mm) and silt (0.002-0.02 mm) soils have high water-holding capacity and capillary rise height and must be drained due to their risk of silting (Eriksson et al. 2011; Weidow 2018).

An envelope is not necessary when drains are installed in stable, structured soil (Stuyt et al. 2005). For example, clay soils with over 25% clay are considered stable and do not risk clogging the pipes. (Wright & Sands 2001). However, clay soils have poor permeability and retain large amounts of water, which means they have a strong need for drainage (Weidow 2018). An envelope can then increase permeability and improve drainage function. Due to the poor permeability of clay soils, increased rainfall from climate change can create problems, as it will take longer for water to reach the drainage pipe compared to other soils (Swedish Board of Agriculture 2010).

High iron levels in soil water can oxidise and precipitate when exposed to air, forming iron ochre that clogs drainage pipes as a reddish-brown, jelly-like mass. This often occurs in mud marshes and sulphide soils, but not in sandy, clay or deep peat soils, where iron deposits are less likely. Factors influencing iron ochre formation include topography, soil type and hydrology. It is crucial to assess the risk of iron ochre deposits before installing drainage by observing open ditches, water appearance and soil deposits, and measuring pH and iron ions in groundwater (Berglund 1984). In iron-rich soils, sawdust should be used as an envelope. Gravel can react with iron-ochre deposits to form a hard, concrete-like layer (Swedish Board of Agriculture 2018).

2.3 Maintenance of the drainage system

Maintaining the existing drainage system is essential and can extend its life (Swedish Board of Agriculture 2012). This can be easily carried out by checking that there are no blockages at outlets and open and blind inlets in the drainage system (Swedish Board of Agriculture 2018). When silting pipes, the pipes can be flushed, and sediment and other material that may obstruct water flow can be removed (Dräneringscentralen rf 2001; Swedish Board of Agriculture 2018). The effect of flushing the pipes depends on the water pressure of the nozzle, the angle of the water jet, and the amount of water used (Dräneringscentralen rf 2001). No intervals are given for how often this needs to be done; local conditions control it (Swedish Board of Agriculture 2018).

2.4 Turbidity

Turbidity is a measure of how much water loses transparency due to suspended particles, such as sediments, inorganic suspended matter, organic matter, soluble organic compounds, phytoplankton, algae, and other microscopic organisms (Sahoo & Anandhi 2023). You can also say that turbidity is a measure of how cloudy the water is. It is influenced by several factors such as human activities, animals or natural processes. Dissolved inorganic chemical elements, organic matter content, and water temperature can all affect water turbidity (Kitchener et al. 2017). In general, turbidity also increases when it rains. The unit used for turbidity is Formazin Nephelometric Unit (FNU) (Sahoo & Anandhi 2023).

Suspended sediment is what affects turbidity the most in aquatic systems and is, in general, correlated with turbidity. The turbidity can therefore be used as an indicator of sediment concentration (Sahoo & Anandhi 2023).

2.5 Nutrient leakage and water quality

Agriculture is the largest source of nutrient leaching into the environment. Its extent is affected by several factors, including crop nutrient uptake, soil type, tillage, use of cover crops, type of fertiliser, timing of application and application rate (Rashmi et al. 2017; Wallman & Delin 2022). The leakage is also controlled by climatic conditions, especially precipitation and temperature (Rashmi et al. 2017).

Nitrogen in soil exists as nitrate and ammonium. Ammonium leaching is minimal because of nitrification, which converts ammonium into nitrate in two steps. Ammonium also binds to negatively charged soil particles, limiting leaching. Nitrate, being an anion, is more mobile and only weakly binds to soil particles and can therefore more easily be transported with the water. Nitrogen leaching risks are higher in soils with high nitrate levels. High soil water content increases the risk of denitrification and nitrous oxide emissions (Eriksson et al. 2011).

Phosphorus primarily exists in soil-bound forms, with only a small, mobilisable fraction available to plants. In acidic soils, it adsorbs to iron and aluminium oxides, while in calcareous soils it precipitates with calcium ions (Rashmi et al. 2017). Dissolved in the soil fluid, phosphorus as dihydrogen phosphate (H_2PO^{4-}) and hydrogen phosphate (HPO_4^{2-}) occur in very low amounts up to about 2 mg P/l. In arable soil, the concentration of phosphorus in the soil solution can amount to about 0.05 kg per hectare (Eriksson et al. 2011).

3. Materials and Methods

3.1 Site description and cropping system

The experimental site is located in Sweden in Mälardalen between Sala and Enköping (N 59° 47'; E 16° 45') on the border between the counties of Västmanland and Uppsala (Figure 1). During the normal period 1991-2020, the location experienced a warm temperate climate (Hellström, S 2021). The average annual temperature is 6-7 °C (SMHI n.d), and the average temperature is +17 °C in July and -3 °C in January (SMHI n.d). The average annual precipitation is 400-600 mm, and the length of the growing season is 190-200 days (SMHI n.d). The soil is clay with 25-40% clay content. Conventional cultivation is carried out on the site with reduced cultivation and direct sowing. In this case, reduced cultivation is to a depth of 12 cm. In the first year of the field trial harrowing was performed before spring wheat was sown on 12 May and fertilised with NPK 300 kg/ha. A second fertiliser application with calcium nitrate 300 kg/ha was made in June. After harvesting the spring wheat, a catch crop of rye and oilseed rape was sown at the end of August. In the second year, a pea crop was sown on 27 April and fertilised with PK 70 kg/ha.

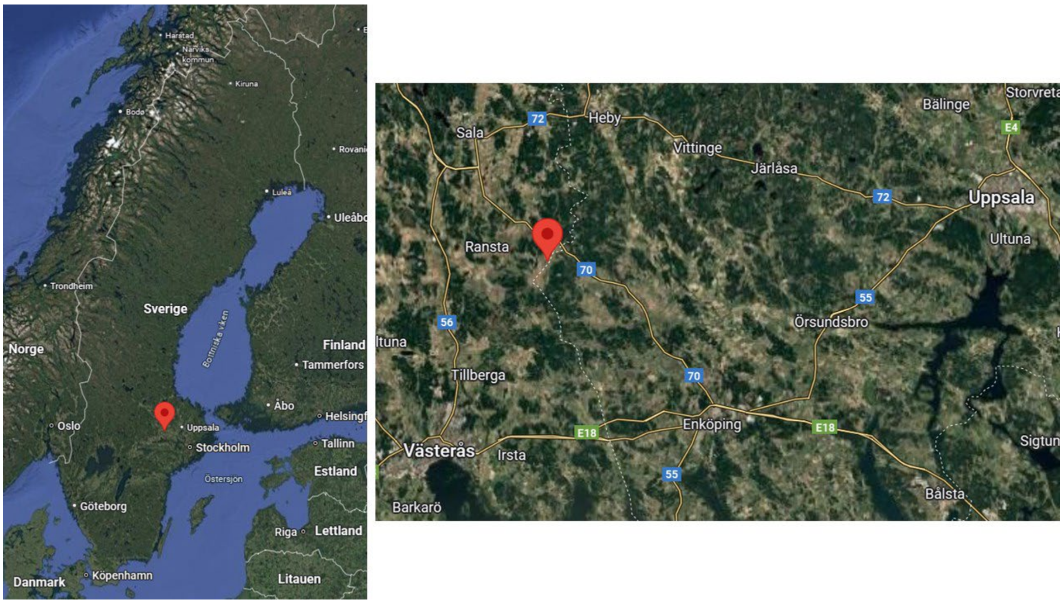
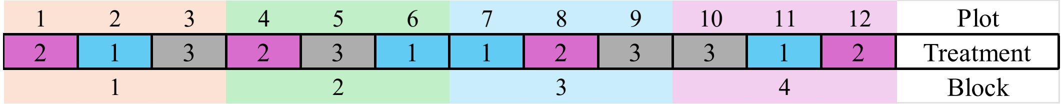


Figure 1. Map showing the location of the field trial, which is in Sweden, between Sala and Enköping (N 59° 47'; E 16° 45') on the border between the counties of Västmanland and Uppsala.

3.2 Field trial design

The field trial was established in 2023 and consists of four randomised blocks with three treatments, each using a different envelope material around the drainage pipe. In total, there are 12 individually drained plots (Figures 2 and 3). The three different treatments are:

1. Perforated drainage pipe without envelope material (Blue)
2. Perforated drainage pipe with thick recycled fibre envelope (Purple)
3. Perforated drainage pipe with crushed rock (4-8 mm Ø) in the backfill (Grey)



1	2	3	4	5	6	7	8	9	10	11	12	Plot
2	1	3	2	3	1	1	2	3	3	1	2	Treatment
1			2			3			4			Block

Figure 2. Distribution of plots 1-12 and treatments 1-3 in 4 blocks in the field trial. Treatment 1 (blue) is a perforated drainage pipe without envelope material. Treatment 2 (purple) is a perforated drainage pipe with a thick recycled fibre envelope, and treatment 3 (grey) is a perforated drainage pipe with crushed rock (4-8 mm Ø) in the backfill.

All plots are 80 metres long and 8 metres wide, with the drainage pipe (Ø 58/50) placed in the middle. Between each plot, there is a cut-off drain (Ø 58/50) at the same drain spacing as in the plots, but in the opposite direction, leading to the ditch south of the field experiment (Figure 3). From each plot, the water is led in tight pipes (PE-50 mm "sewer pipes") to a measuring station at the western ditch, where turbidity and flow measurement and water sampling are performed using modern technology (see below).

Figure 3. Map over the field trial where (1) is a perforated drainage pipe without envelope material, (2) is a perforated drainage pipe with a thick recycled fibre envelope and (3) is a perforated drainage pipe without envelope material with crushed rock (4-8 mm Ø) in the backfill. There are 16 metres between every drainage pipe. Between every drainage pipe is a cut-off drainage pipe.

Water flow measurement from the drainage system is carried out using a two-sided tipping bucket (Figure 4), with each side possessing a volume of about 4 litres. A data logger continuously records every tipping event, enabling calculation of the total subsurface runoff. The collected data is summarised and aggregated at an hourly resolution. Data from the data logger is transmitted via modem. The data used in this work were collected during the two hydrological years 2023-2025.

The data logger also controls the extraction of flow-proportional water samples. When a predetermined volume of water has passed, a hose pump is activated that extracts a small amount of water from the incoming pipe. These sub-samples are collected into a single sample, which is analysed every 14 days.

The hose pumps are at the measuring station, while the test canisters are stored in a cool, dark room in the measuring station's basement. The collected aggregated water samples are analysed for phosphorus and nitrogen content, sediment and turbidity at the Department of Aquatic Sciences and Environment at the Swedish University of Agricultural Sciences, SLU. Total N is analysed using the catalytic oxidative combustion method, and total P is analysed by spectrophotometry with ammonium molybdate according to the ISO standard (SLU 2025).

Figure 4. The two-sided tipping buckets from four of the drainage pipes of the plots in the field trial. Photo: Linnea Berggren Sjögård

3.3 Excavation - Collection of samples

Excavation of a section of the drainage pipes was carried out on 23 and 24 September 2025 in the field trial, as illustrated in Figure 5. An excavator was used to dig down to the drainage pipe, about 120 cm down. Subsequently, small shovels were used to expose about 50 cm of the pipe. Observations about the soil moisture around the pipe were made, and pictures were taken for documentation. For each drainage pipe (a total of 12), a soil sample (a cube of 8*8*8 cm) was taken from the soil directly above the pipe or from the gravel placed in plastic bags. Following this, 40 cm of the drainage pipe was sawn off with a fine-toothed saw for observation and sampling of sediment accumulated within the pipe. In trial treatment 2, the wrapped recycled envelope material was cut where the pipe was to be sawn off. Plugs were inserted at each end of the 40 cm-long sawn pipes before they were placed in a plastic bag. For each repetition of treatment 3, a sample of the envelope material (crushed rock) was also collected and put in a plastic bag. The drainage pipe was joined with a 40 cm section of new drainage pipe and two socket fittings (Figure 5, below right), and the pits were closed.

Figure 5. Pictures showing the excavation of the pipes in chronological order. Above left: excavation machine, mid above: soil profile, right above: the soil sample has been taken. Below left: exposed pipe, mid below: 40 cm of pipe cut off, right below: the joint pipe. Photo: Linnea Berggren Sjögård

3.4 Laboratory work

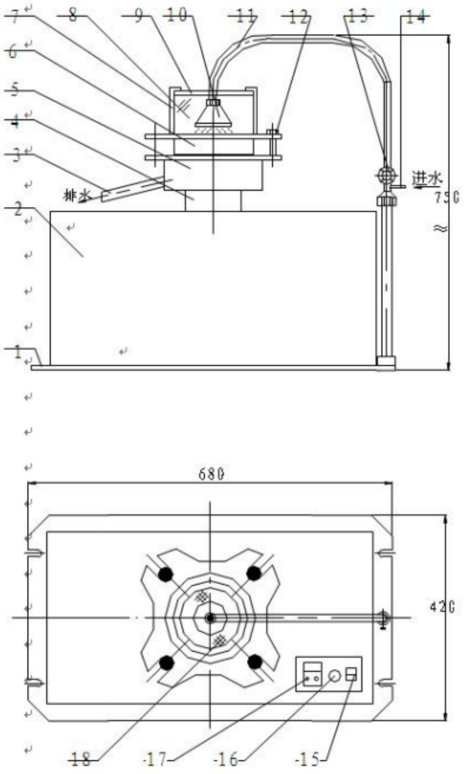
3.4.1 Collection of soil inside the drainage pipes

The pipes collected from the excavation were placed in trays, one tray per treatment. Photos of the inside of every pipe were taken. They were then placed in a drying room until they were completely dry. This took around 12 to 24 hours for treatment 1 (no envelope) and treatment 3 (crushed rock envelope), and 4 days for treatment 2 (synthetic envelopes).

After drying, the pipes were cleaned on the outside with a brush. The pipes were then cut into two parts to see how much soil was inside. Photos of the sediment inside the pipes (Figure 12) were taken before they were brushed clean. The soil from inside was collected and weighed.

3.4.2 Testing of the synthetic envelopes

To determine the size of particles that pass through a synthetic drain envelope, the envelope opening size was tested. The machine used for testing was a TESTEX TG030 Geotextile opening size tester (wet sieving), as shown in Figures 6 and 8. The envelopes that were tested, PP-450, come from MST Draintechnics (MST 2025). The synthetic envelope around the drainage pipe was cut along the pipe to free the envelope from the pipe. A template of the sieve size of the machine TG030 Geotextile opening size tester was then used to cut the envelope to a suitable size for the machine (Figure 7). The area of the tested sample surface was 21.5 cm. Four circular pieces of the synthetic envelope were cut from an unused envelope and labelled A, B, C and D. Four pieces of the synthetic envelope were also cut from each drainage pipe from the field, plots 1, 4, 8 and 12. The dry weight of the cut envelopes was taken.



1. Foundation
2. Cover
3. Exhaust water pipe
4. Shaking head
5. Collecting sieve
6. Clamping device
7. Hasp
8. The transport cover
9. Antisplash cover
10. Shower head
11. Metal hose
12. Bolt
13. Flow control valve
14. Water inlet
15. Power
16. Start
17. Timer
18. Sieve

Figure 6. Sketch of the TG030 Geotextile opening size tester (wet sieving). The lower part of the sketch shows the machine from above (Testex n.d).

Prior to testing, envelopes A-D were soaked in water for more than 12 hours. It was not possible to soak the envelopes from the field, as much of the soil would have been lost. Instead, the dry envelopes were placed on the sieve and sprayed with water for around 10 seconds to make them completely wet. The test was performed on one envelope at a time. The envelope was placed in the machine on the sieve (Figure 7). According to the manual, 50 g of standard granular material was evenly spread on the surface of the envelope (Testex n.d.). The granular material selected for envelopes A-D had a mesh size of 60, corresponding to a particle size of 0.25 mm. The granular material was then wetted. The time was set to 10 minutes, and the water flow to 500 ml min^{-1}, according to SS-EN ISO 12956:2020. During the test, water sprays from above through a nozzle, and the sieve on which the envelope is placed is shaking (Figure 8). During the test, the water and particles that passed through the synthetic envelope were collected through a filter/mesh to collect the particles before the water was collected in a container. After testing, the envelopes were placed in an oven at 105 °C until they were completely dry, for around 6 hours. The particles from the water trapped in the filter were dried at room temperature. The dry weights of the envelopes and the particles were measured.

Figure 7. The diameter of the sieve of the machine to the left and the cut envelope in the sieve. Photo: Linnea Berggren Sjögård

The data for the synthetic envelopes A-D were calculated in Excel using the table from ISO 12956:2020 (Table 5). The particle size distribution of the granular material used was tested with Partica Laser Scattering Particle Size Distribution Analyser LA-950-V2 to see if the actual particle size matched the specified particle size. The characteristic opening size, O_{90}, of the synthetic envelope was determined graphically from the graph of the particle size distribution of the granular material (Figure 14).

For the synthetic envelopes from the field, the calculations of the soil loss were determined from the change in envelope mass (Calculated loss). To verify this, the sediment in the throughflow water was collected and weighed (Measured loss). The discrepancy between these two values was defined as the recovery loss, expressed in grams and as a percentage (Table 7).

Figure 8. The machine TESTEX TG030 Geotextile opening size tester (wet sieving) is in process. Photo: Linnea Berggren Sjögård

3.4.3 Laser scattering particle size distribution

The soil collected from inside the drainage pipes and the soil filtered from the synthetic envelopes tested in the field were prepared for particle size distribution analysis. The soil was placed in 7 beakers. Beakers 1-4 contained filtered soil from the synthetic envelope test, and beakers 5-7 contained soil from inside the drainage pipes. Approximately 10 ml of deionised water was added. Following this, around 5 ml of hydrogen peroxide (H_2O_2) was added, and they had to stand overnight to allow the reaction to proceed. The next day, the beakers were boiled for 6 hours and then left to stand overnight. The contents of the beakers settled, and the water on top was removed with a pipette. Plastic from the synthetic envelope was removed with tweezers if necessary. The soil samples were then transferred to plastic cups with lids, and a dispersing liquid was added before they were placed in a shaker for overnight dispersion.

The following day, the soil samples were transferred from the plastic cups to glass beakers, and deionised water was added until the contents reached 300 ml. The beaker was placed on a magnetic stirrer to prevent sedimentation of the sample.

The laser scattering apparatus used was Partica Laser Scattering Particle Size Distribution Analyser LA-950-V2. A sample was taken from the centre of the beaker using a pipette and transferred to the laser scattering apparatus, which then analysed it. For each cup, 3-4 analyses were performed. For beakers 5, 6 and 7, which contained soil from inside the pipes, wet sieving was performed when the samples were transferred from the plastic cups to the glass beakers, as larger plastic pieces were present in the samples. There were remnants from the perforating of the pipes, and when the pipes were sawn off and taken out of the soil during the excavation.

3.5 Statistics

Excel was primarily used for data management, calculations and statistics. The following statistical methods were used: one-way ANOVA, Tukey HSD and regression. For the ANOVA analyses, the significance level was 0.05. ANOVA was performed in Excel on soil samples collected from each pipe within each treatment, and on turbidity alone, to determine whether there were any significant differences among the treatments. In the TIBCO® Data Science / Statistica™ program, ANOVA and Tukey HSD tests were performed on sediment from inside the drainage pipes and on total P and N concentrations. To examine relationships and correlations among turbidity, suspended material and Total P concentration, simple linear regression analyses were used. The R^2 coefficient was calculated to assess the strength of these correlations.

4. Results

4.1 Results related to dug-out drainage pipes

4.1.1 Excavation - observations

The plots generally had a similar soil water content (Table 1), and all were classified as moist. Only minor differences separated the plots. Plots 7, 8 and 9 (block 3) stood out as noticeably less moist than the others. In these plots, when performing a clay consistency test, it was only possible to form a dry clay soil ball, whereas the other plots produced muddy soil balls. In plot 7, the reduced moisture may be explained by the old tile drain intersecting the new pipe at the sampling point (Figure 9).

The presence of water beneath the pipe varied across plots. No water was observed under the pipe in plots 6 and 7 in treatment 1, in plot 8 in treatment 2 and in plots 5 and 9 in treatment 3 when digging. In plots 1-4 and 10-12, water came up during digging. Additionally, plots 5-9 did not exhibit standing water at the sampling point during the follow-up inspection shortly after excavation, about 1 hour later. In plot 6, a flat, hard, whitish surface was observed in certain parts of the pit at the same depth as the drainage pipe, approximately 1 m (Figure 10).

Table 1. Compilation of notes from the excavation of the 12 plots divided into the following categories: Moisture around pipe, soil consistency (possible to form a ball), presence of water under the pipe when digging, standing water in the pit during follow-up inspection and comments from the field.

Treatment	**Plot**	**Moisture around the pipe**	**Soil Consistency**	**Water (digging)**	**Water (follow-up)**	**Notes**
1	2	Moist	Muddy ball	Yes	In between	
1	6	Moist	Muddy ball	No	No water	Feels drier than block 1. Presence of a hard flat surface in some places in the pit
1	7	Not very wet	Dry ball	No	-	Old brick pipe collides with the pipe
1	11	Moist	Muddy ball	Yes	In between	
2	1	Moist	Muddy ball	Yes	-	
2	4	Moist	Muddy ball	Yes	A lot	Same as plot 1
2	8	Not very wet	Ball – not dry, not muddy	No	-	Not very wet, but you can hug the ball, more muddy ball here than in plot 7
2	12	Moist	Muddy ball	Yes, but not much	A little	Iron deposit
3	3	Moist	Muddy ball	Yes	A little	Hard to see if it's as humid as the previous plots because of the gravel
3	5	Moist	-	No	No water	A little drier because of the gravel?
3	9		Dry ball	No	A little	
3	10	Moist	Muddy ball	Yes		Iron deposit

Figure 9. The picture shows how the new drainage pipe cuts through the old brick pipe in plot 7. Photo Linnea Berggren Sjögård

Figure 10. Plot 6, to the right of the pipe there is a flat, hard, whitish surface at the same depth as the drainage pipe, approximately 1 m. Photo: Linnea Berggren Sjögård

When sawing off the drainage pipes, pipes without an envelope (treatment 1) appeared to contain more sediment than treatments 2 and 3, which had synthetic envelopes and crushed rock envelopes. The differences in sediment accumulation among treatments are illustrated in Figure 11. Treatment 1 (no envelope; shown at the top of Figure 11) contains the largest amount of sediment, particularly in plot 11 (upper right in Figure 11).

For treatment 2 (synthetic envelope), the black colouring of the pipe made it difficult to visually assess the sediment content. However, small amounts of sediment were visible within the pipe recesses. Treatment 3 (crushed rock envelope; shown at the bottom of Figure 11) exhibited only minor sediment accumulation, which was predominantly confined to the pipe recesses and was considerably lower than the sediment levels observed in treatment 1 (no envelope).

Figure 11. Picture of the inside of the drainage pipes from the excavation. Top: treatment 1 (no envelope) - plots 2, 6, 7 and 11. Middle: treatment 2 (synthetic envelope) - plots 1, 4, 8 and 12. Bottom: treatment 3 (crushed rock envelope) - plots 3, 5, 9 and 10. Photo: Linnea Berggren Sjögård

4.1.2 Collection of soil inside the drainage pipes

The pipes from treatment 2 (synthetic envelope) possessed the smallest amount of soil, 0.89 grams per 40 cm pipe, on average (Table 2), while treatment 3 (crushed rock envelope) had an average of 2.10 grams. Treatment 1 (no envelope) had the highest amount of soil inside the pipes, 5.94 grams on average, which was significantly higher than the other two treatments (Tables 2 and 3). The average value of treatment 3 is only based on three values. The soil sample plot 5 was discarded because it was the first pipe to be processed and was used to standardise the cleaning procedure.

Table 2. The average weight of the soil collected from inside the drainage pipes from treatments 1, 2 and 3.

Envelope	Treatment	Soil inside pipe (g per 40 cm pipe)
No envelope	1	5.94 a*
Synthetic	2	0.89 b
Crushed rock	3	2.10 b

* Different letters indicate significant differences according to Tukey´s HSD test ($p \leq 0.05$)

An ANOVA analysis was performed on the weight of soil samples collected from each pipe within each treatment (Table 3). The obtained *p*-value (0.000925) was below the significance level of 0.05, and the calculated *F*-value surpassed the critical *F*-value.

Table 3. Results of ANOVA analyses of weight of soil collected from inside each pipe in each treatment, showing the: Sum of squares (SS), Degrees of freedom (df) and Mean square (MS), both between and within groups. The F value is the mean square between groups divided by the mean square within groups. A p-value lower than 0.05 indicates a statistically significant correlation.

Variation origin	*SS*	*df*	*MS*	*F*	*p*-value	*F*-crit
Between groups	54.653	2	27.326	18.938	0.000925	4.458
Within groups	11.543	8	1.442			
Total:	66.1964	10				

The weight of the soil inside the pipes also reflects what the pipes looked like on the inside before the soil was collected from them, as visualised in Figure 12. Treatment 1 (no envelope) contained the most soil inside, whereas treatment 2 (synthetic envelope) had the least amount of soil and only very small particles.

Figure 12. Demonstrates the amount of soil inside the pipes when they were cut open before cleaning. From left to right, treatments 1 (plots 2, 6, 7, 11), 2 (plots 1, 4, 8, 12) and 3 (plots 5, 9, 10). In treatment 3, the pipe from plot 3 was not photographed. Photo: Linnea Berggren Sjögård version

The percentages for each particle size according to the Atterberg scale are presented in Table 4. Treatment 1 had the largest proportion of particles in the size range of 0.002-0.006 mm, fine silt. Treatment 2 had the most particles in the size range of 0.0002-0.002 mm, coarse clay. Treatment 3 primarily contained particles of intermediate sand 0.2-0.6 and fine sand 0.06-0.2. The particle size that poses the greatest risk of clogging the pipes is 0.06-0.15 mm, which corresponds to fine sand in Table 4. Treatment 3 (crushed rock envelope) had the largest proportion of these particle sizes, 21.3%.

Table 4. The average percentage of each particle size for each treatment. The particle size distribution scale is according to the Atterberg scale.

Particle size name	**Size class (mm)**	**Treatment 1 %**	**Treatment 2 %**	**Treatment 3 %**
Colloidal clay	<0.0002	3.4	2.4	0.4
Clay	0.0002-0.002	27.8	45.3	11.2
Fine silt	0.002-0.006	20.9	24.4	9.6
Medium silt	0.006-0.02	18.0	18.1	11.6
Coarse silt	0.02-0.06	20.1	6.1	10.1
Fine sand	0.06-0.2	9.1	3.4	21.3
Medium sand	0.2-0.6	0.7	0.3	34.3
Coarse sand	0.6-2	0.0	0.0	1.4

Laser scattering particle size distribution analysis confirms the observations and the weight of the soil in treatment 2 (synthetic envelope). Treatment 2 had the highest number of small particles while treatment 3 (crushed rock) had the highest number of large particles (Figure 13).

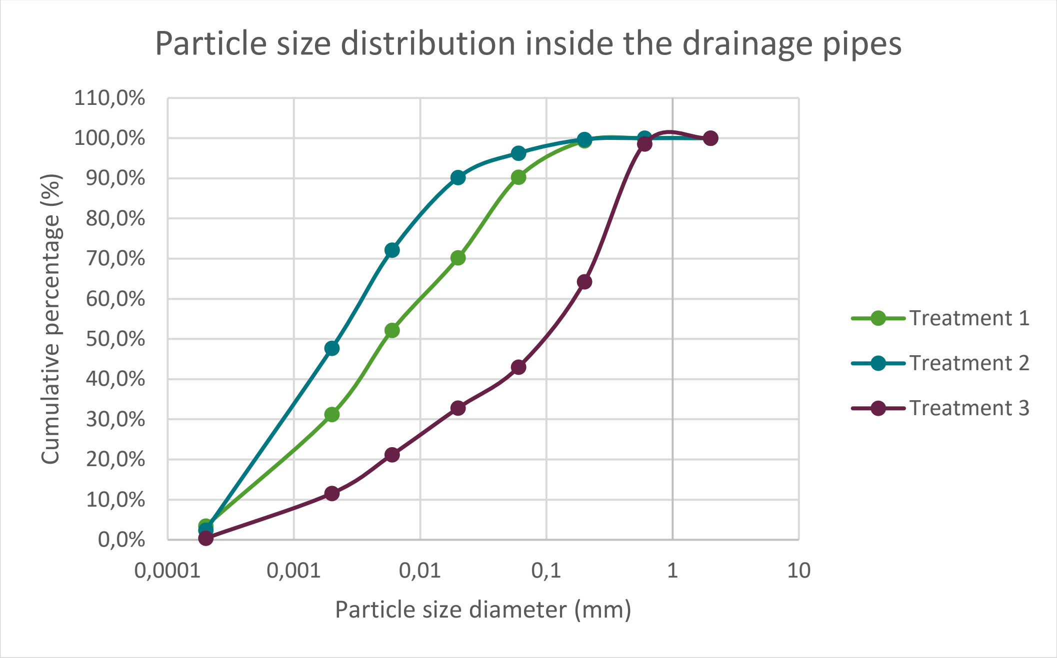


Figure 13. Particle size distribution from the laser scattering particle analysis of the soil from inside the drainage pipes in treatments 1, 2 and 3.

4.1.3 Testing of the synthetic envelopes

Laboratory testing of unused synthetic envelope

The results for envelopes A-D were documented in Table 5 in accordance with SS-EN ISO 12956:2020. In Table 5, under granular material, initial (1) shows the weight of the granular material added to the envelope prior to testing. Passed (2) shows the weight of the material that runs and passes through the envelope with the water. Retained (3) shows the weight of the material that remained in the envelope. The difference between each sample and the sample average is shown in the rightmost column. According to the ISO 12956:2020 standard, the tests are approved if the deviation is less than 15%. It also states that if the passed granular material is less than 30 g for three specimens, two more tests should be conducted. Three out of four specimens had more than 30 g of passed granular material.

Table 5. Table according to ISO 12956:2020 showing the initial (1) weight of the granular material added to the envelope before testing. Passed (2), which is the weight of the material that runs and passes through the envelope with the water. Retained (3) is the weight of the material that remained in the envelope. pi is the passed granular material for each specimen, and p is the mean value of all the specimens. The rightmost column shows how much the tests differ from each other and should not exceed 15%.

Test	Granular material				Lost granular material 100[(1)-(2)-(3)]/(1)	Passed granular material 100[(2)/(1)]	p-pi	[(p-pi)/p] *100
	Initial (1)	Passed (2)	Retained (3)	Total (2+3)	%	%	%	%
1	50	33.43	13.95	47.38	5.24	66.86	-0.045	0.067
2	50	38.64	12.95	51.59	-3.18	77.28	-10.46	15.66
3	50	27.64	22.16	49.8	0.4	55.28	11.53	17.26
4	50	33.92	15.84	49.76	0.48	67.84	-1.025	1.534
Total	200	133.63	64.9		**Mean:**	66.82		

The particle size distribution of the standard granular material from the laser scattering analysis is illustrated in Figure 14. Samples 1, 2 and 3 are very similar in the particle size distribution. Most of the particles are the same size, which can be seen from the steep slope of the curve.

66.82% of the granular material passed through the synthetic envelope (Table 5). The characteristic opening size, O_{90}, was determined graphically at 60% (0.9*66.82), giving O_{90} = 0.4 mm (Figure 14). 90% of the particles that passed through the synthetic envelope were smaller than 0.4 mm. The synthetic envelope should stop 90% of all particles larger than 450 microns, which is equivalent to 0.450 mm, according to the manufacturer (MST 2025). The chosen granular material had mesh size of 60, corresponding to a particle size of 0.25 mm. The particle size distribution from laser scattering analysis reveals that the mean particle size was 0.381 mm (Table 6).

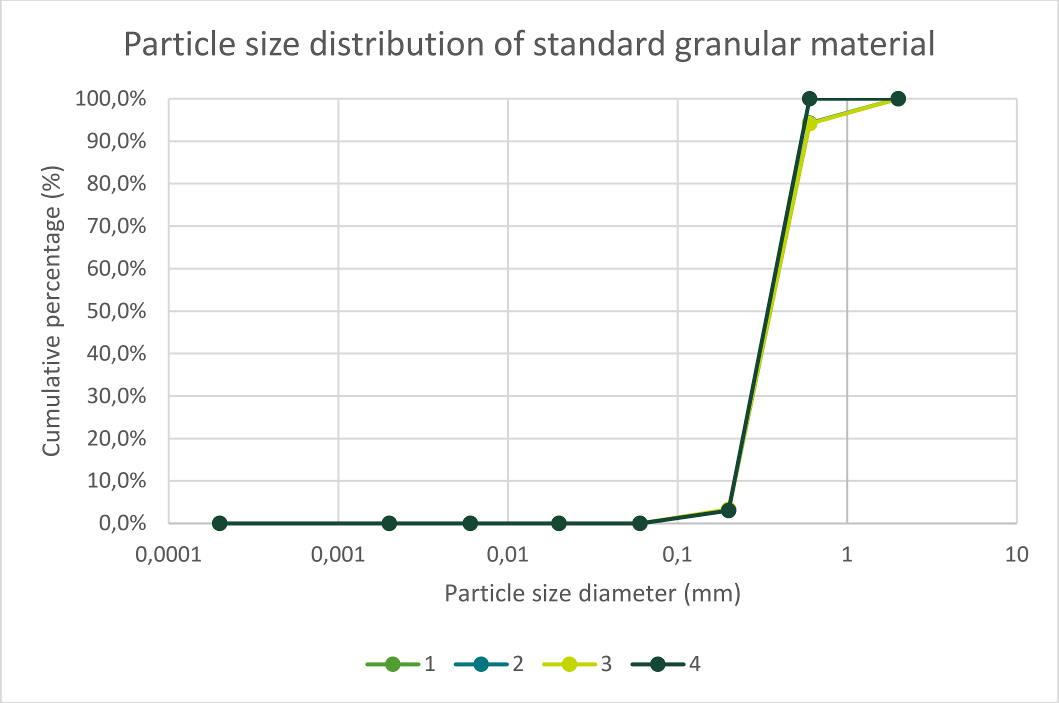


Figure 14. Particle distribution of the standard granular material used in the unused synthetic envelope test. The material was said to be in mesh size 60, which corresponds to 0.25 mm.

Table 6. Mean value of the particle size of the standard granular material from the laser scattering analysis.

Sample	**Mean (µm)**	**Mean (mm)**
1	381.463	0.381
2	381.284	0.381
3	381.192	0.381
4	383.475	0.383
Average	**381.854**	**0.381**
Mesh 60	**250.000**	

Laboratory testing of the synthetic envelopes from the field

Since the envelopes came from the field (treatment 2), it was not possible to determine the weight of the envelopes alone, without any soil inside. Therefore, the table from the standard ISO 12956:2020 was not used in this test.

Soil particles passed through the envelope during the test, as indicated by the decreased envelope weight after testing (Table 7). The calculated mean amount of soil transported through the envelope was calculated by weighing the synthetic envelopes before and after the lab test. The calculated amount was 12.03 g, while the actual measured amount was 11.28 g. This resulted in an average loss of 0.74 g during the testing process, corresponding to 6.69% of the calculated soil content.

Plots 1 and 4 contained the highest number of particles in the size range 0.002-0.006 mm (fine silt), and plots 8 and 12 contained the highest number of particles in the size range 0.0002-0.002 mm (clay) (Table 8). Moreover, the pipes possessed a small number of particles that risked clogging the envelope (0.05-0.15 mm). Plots 8 and 12 contained a larger proportion of such particles (0.06-0.2 mm) than plots 1 and 4 did.

Table 7. The weight of the synthetic envelopes from treatment 2 before (initial mass) and after (final mass) testing, and the calculated soil content from the water that runs through the envelope (calculated loss). The weighted amount of soil from water that runs through the envelope (measured loss). The difference between the calculated and the weighted amount of soil from water that runs through the envelope (difference).

Plot	**Initial mass (g)**	**Final mass (g)**	**Calculated loss (g)**	**Measured loss (g)**	**Difference (g)**	**Difference (%)**
1	38.12	29.94	8.18	7.58	0.6	7.33
4	39.87	31.65	8.22	7.66	0.56	6.81
8	48.78	29.94	18.84	18.23	0.61	3.24
12	53.33	40.45	12.88	11.67	1.21	9.39
Mean:	45.02	32.99	12.03	11.28	0.745	6.69

Table 8. Particle size distribution of soil from the water that runs through the synthetic envelope from the field from each plot in treatment 2 (synthetic envelope), in percentage.

Particle size name	**Size class (mm)**	**Plot 1 (%)**	**Plot 4 (%)**	**Plot 8 (%)**	**Plot 12 (%)**
Colloidal clay	<0.0002	3.3	5.6	2.8	2.1
Clay	0.0002-0.002	20.6	30.8	24.2	24.7
Fine silt	0.002-0.006	41	31.1	23.6	19.1
Medium silt	0.006-0.02	25.1	21.2	20.4	20.2
Coarse silt	0.02-0.06	6.6	8.4	16.2	17.7
Fine sand	0.06-0.2	3.1	2.8	11.7	15.6
Medium sand	0.2-0.6	0.6	0.2	1.1	0.6
Coarse sand	0.6-2	0.0	0.0	0.0	0.0

Plots 1 and 4 demonstrated a similar particle size distribution, with a high proportion of fine particles below 0.1 mm (Figure 15). Plots 8 and 12 had a more linear curve, indicating a more gradual increase in cumulative percentage and suggesting that they contained coarser particles compared to plots 1 and 4. All curves start at the same point, showing that all samples include particles from the same size range.

A comparison was made between the particle size distribution of the soil that passed through the synthetic envelopes and the particle size distribution of the standard granular material from the testing in Section 4.1.2 (Figure 15). The soil that has passed through the envelope has a larger proportion of finer particles compared to the granular material, whose average particle size is 0.381 mm. This is consistent with the point on the curve where the granular material exhibits a sharp slope, indicating a rapid increase in the cumulative proportion within this size range, which is quite consistent with where the curve gets a strong slope.

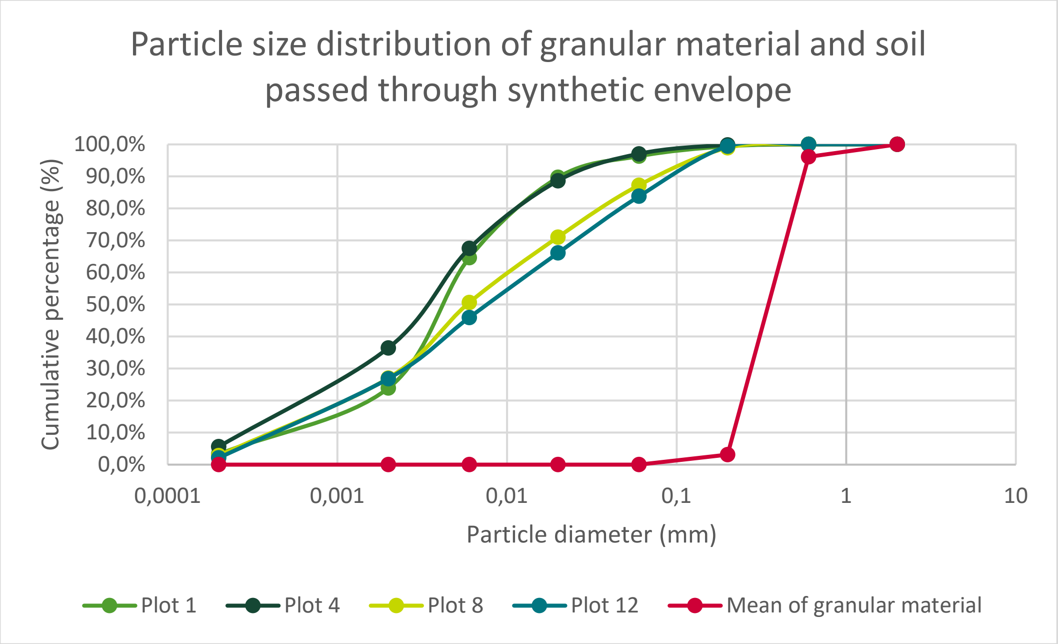


Figure 15. Comparison between the particle size distribution from laser scattering particle size analysis of granular test material and soil passed through the synthetic envelopes in treatment 2, plots 1, 4, 8 and 12.

4.2 Report and analysis on time series data

4.2.1 Turbidity

Figures 16 and 17, showing turbidity and suspended material, respectively, illustrate how these parameters vary over the years. The turbidity in 2023-2024 was high in October, reaching its lowest value in December. In February, it peaked and then gradually decreased until June 2024. However, this was not the case for treatment 2, which had the highest turbidity in May and June 2024. During 2024-2025, runoff was low, therefore data are only available from December 2024 to March 2025. Throughout this period, turbidity was highest in January 2025, except for treatment 1, which had the highest turbidity in December. The suspended material (Figure 18) follows the same variation as turbidity, except for May and June 2024, when the suspended material for treatment 1 exceeded turbidity.

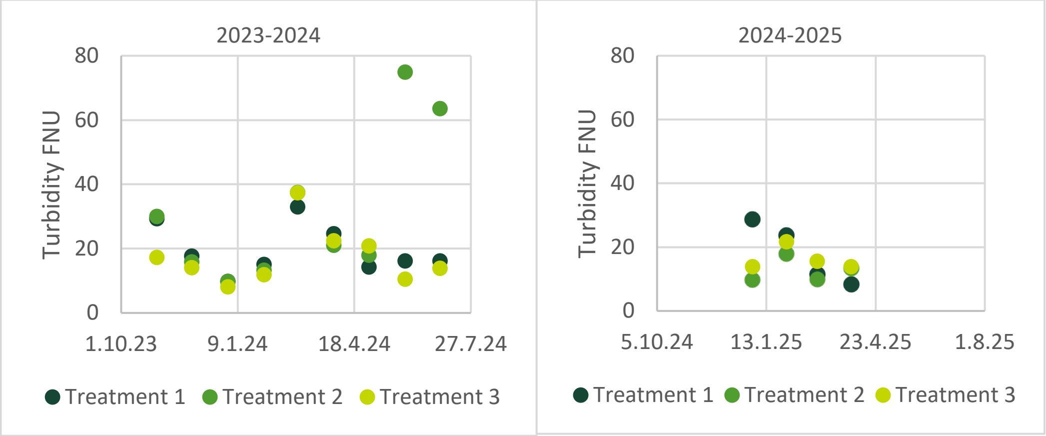


Figure 16. Turbidity for treatment 1, 2 and 3 for the year 2023-2024 (left) and for the year 2024-2025 (right).

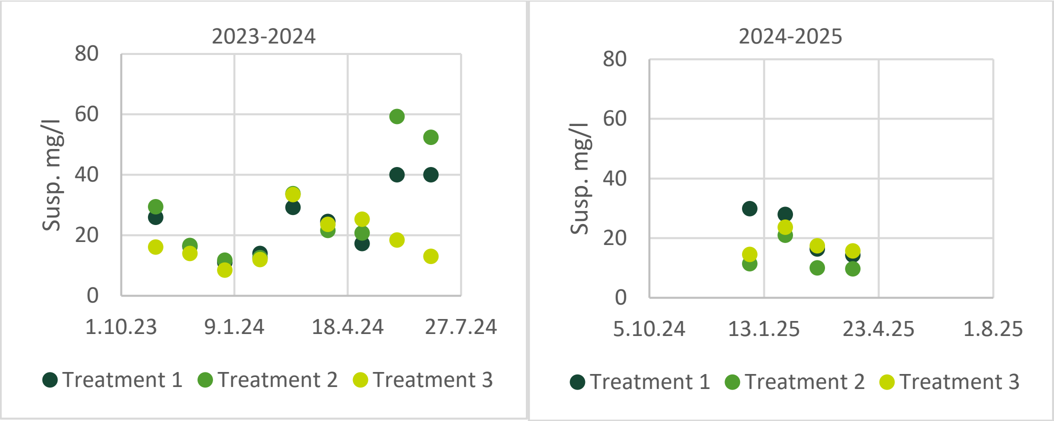


Figure 17. Suspended material for treatment 1, 2 and 3 for the year 2023-2024 (left) and for the year 2024-2025 (right).

An ANOVA was carried out on turbidity across all repetitions in all treatments (n = 99) for the year 2023-2024. No ANOVA was conducted for 2024-2025 due to insufficient values. The results showed no significant difference between the treatments ($F(2.96) = 1.53$, $p = 0.22$). Treatment 2 had a very high variance (3340.52). The mean values for treatments 1, 2 and 3 were 19.56, 31.53 and 17.35 FNU, respectively.

Figures 18 and 19 show the correlation between monthly turbidity and suspended material. In 2023-2024 (Figure 18), treatment 2 (synthetic envelope) had the highest correlation (R^2=0.99), while treatment 3 (crushed rock) also had a high correlation (R^2=0.85). Treatment 1 (no envelope) has the weakest correlation (R^2=0.098). In 2024-2025 (Figure 19), treatments 1 and 3 showed very strong correlations (R^2=0.99 and 0.98), whereas treatment 2 was weaker (R^2=0.74).

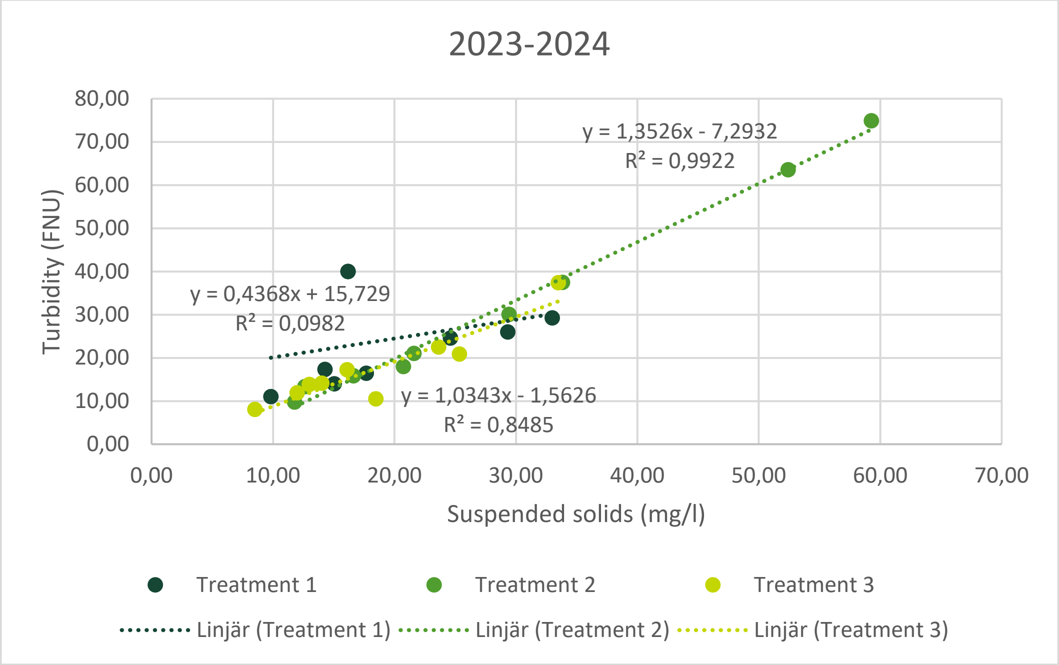


Figure 18. Turbidity and suspended material in the year 2023 – 2024 with trendline, equation and R^2.

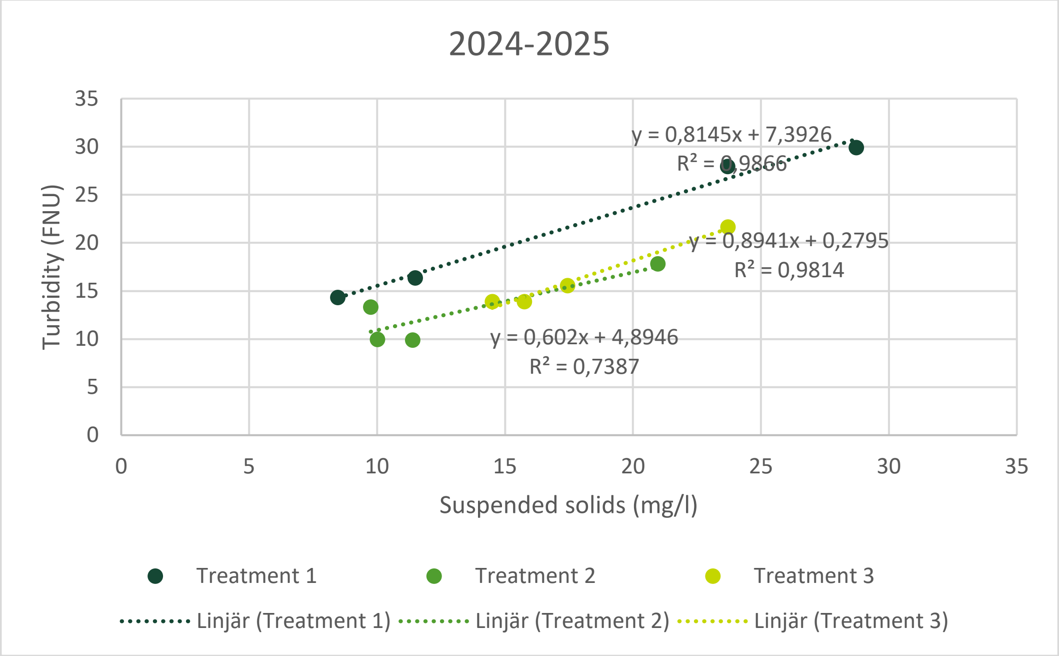


Figure 19. Turbidity and suspended material in the year 2024-2025 with trendline, equation and R^2.

The turbidity and total P measured in 2023-2024 were plotted together in Figure 20, while suspended material and total P were depicted in Figure 21. The correlation between turbidity and total P was strong across all treatments, with R^2 values ranging from 0.82 to 0.97 (Figure 20). Similarly, the correlation between suspended material and total P had R^2 values ranging from 0.79 to 0.97 (Figure 21). Both turbidity and suspended material displayed a strong correlation with total P in treatment 2 (Turbidity/total P $R^2 = 0.97$ and suspended material/total P $R^2 = 0.97$). In 2024-2025, correlations were weaker across all treatments, with R^2 values ranging between 0.35 and 0.79 for total P and turbidity, respectively (Figure 22) and between 0.07 and 0.67 for total P and suspended material, respectively (Figure 23).

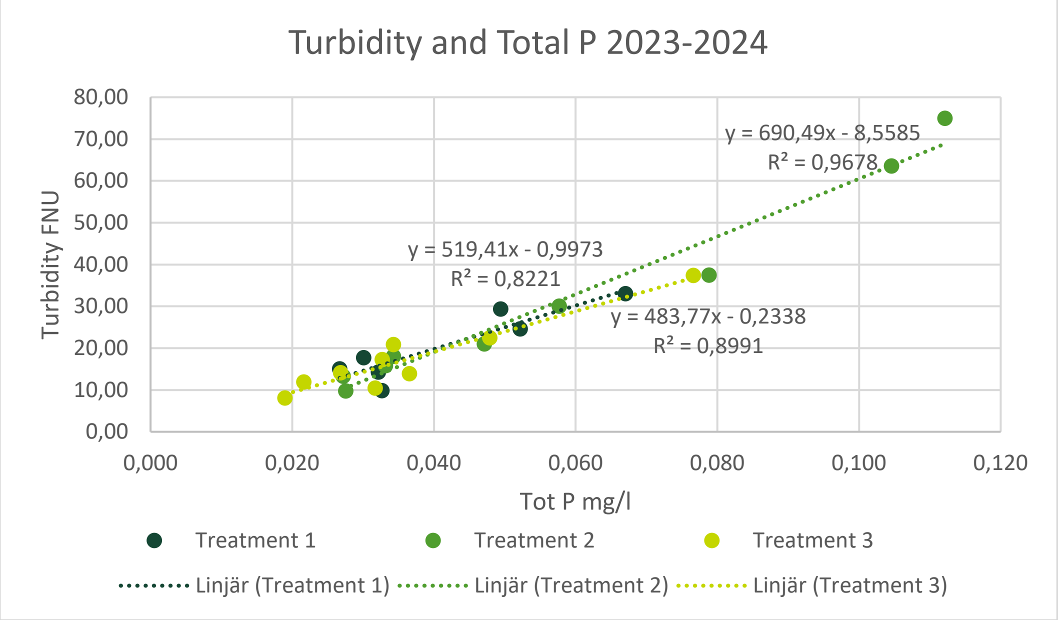


Figure 20. Turbidity and total P in the year 2023-2024 for treatments 1, 2 and 3. R^2 values for treatments 1, 2, and 3 are 0.82, 0.97 and 0.90, respectively.

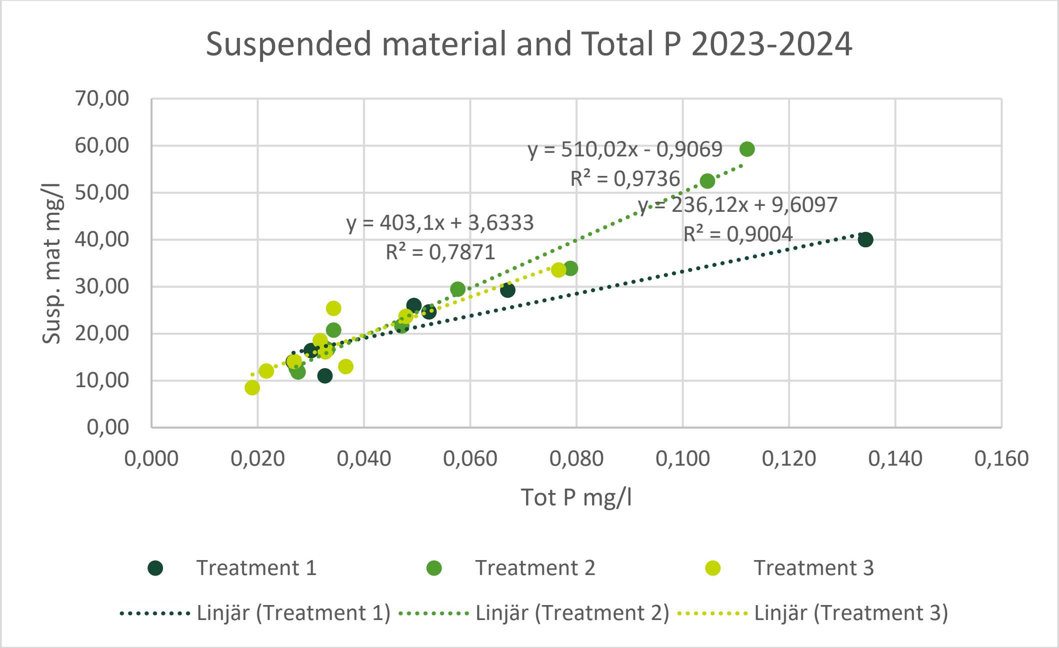


Figure 21. Suspended material and total P in the year 2023-2024 for treatments 1, 2 and 3. R^2 values for treatments 1, 2, and 3 are 0.90, 0.97 and 0.79, respectively.

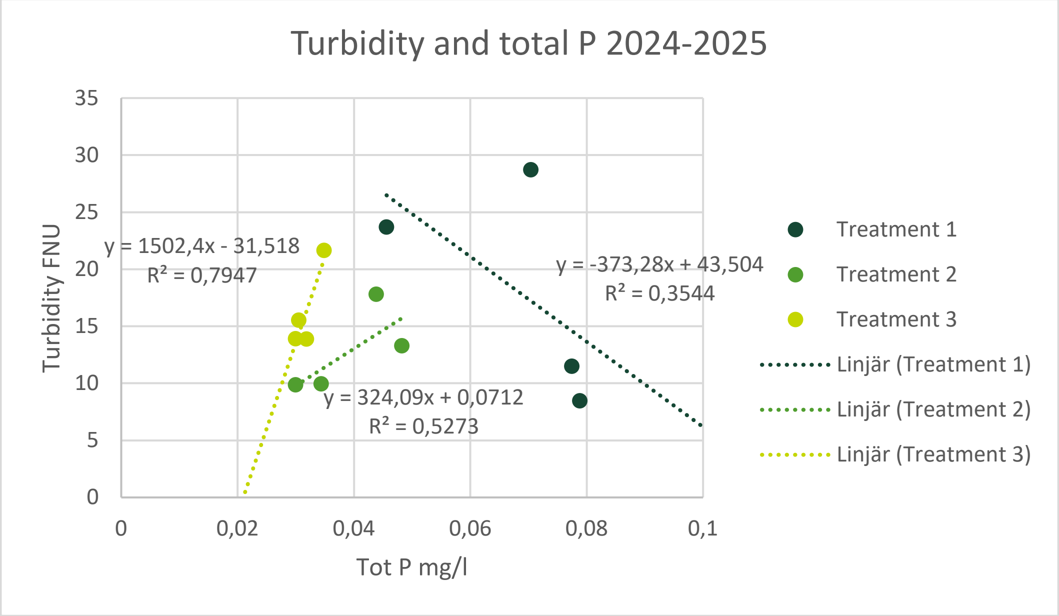


Figure 22. Turbidity and total P in the year 2024-2025 for treatments 1, 2 and 3. R^2 values for treatments 1, 2, and 3 are 0.35, 0.53 and 0.79, respectively.

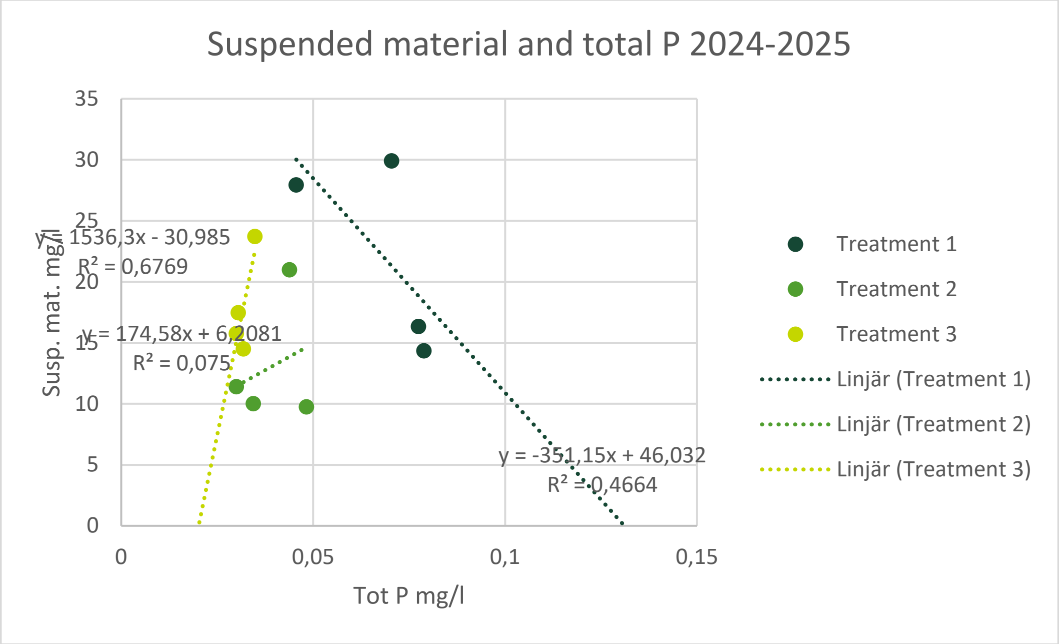


Figure 23. Suspended material and total P in the year 2024-2025 for treatments 1, 2 and 3. R^2 values for treatments 1, 2 and 3 are 0.47, 0.08 and 0.68, respectively.

4.2.2 Subsurface runoff

In the first hydrological year, treatment 2 (synthetic envelope) had the highest annual subsurface runoff, while treatment 1 (no envelope) had the lowest (Table 9). Treatment 3 (crushed rock) was intermediate but showed a notable value in November 2023, compared to other treatments. In March and April, treatment 2 subsurface runoff was higher than treatments 1 and 3, despite low precipitation. These anomalous values may indicate measurement errors. Total subsurface runoff was almost twice as high as the annual rainfall for treatments 2 and 3, while the subsurface runoff for treatment 1 was lower than the corresponding precipitation. The annual precipitation during the study period was generally comparable to the 1991–2020 normal period.

In the second hydrological year, treatment 2 exhibited the highest annual subsurface runoff, which was almost five to six times higher than that of treatments 1 and 3 (Table 10). The largest subsurface runoff occurred in December and January, which together account for most of the hydrological year's total subsurface runoff. During these months, the subsurface runoff for treatment 2 was higher than for treatments 1 and 3. In general, treatments 1 and 3 demonstrated very low subsurface runoff throughout the year, and their annual subsurface runoff was lower both in comparison with treatment 2 and in relation to annual precipitation and normal precipitation. The annual precipitation during the period is largely consistent with the normal values for 1991–2020. In June 2025, subsurface runoff was very low across all treatments, despite the relatively high precipitation this month, 89 mm.

Table 9. Subsurface runoff for treatments 1 (no envelope), 2 (synthetic envelope) and 3 (crushed rock envelope) in the year 2023-2024. Precipitation (P) from the SMHI measurement station in Sala.

2023-2024	Treatment 1 (mm)	Treatment 2 (mm)	Treatment 3 (mm)	P 2023-2024 (mm)	Normal P 1991-2020 (mm)
Oct-23	4.8	4.6	8.1	50.8	56.4
Nov-23	32.9	37.4	144.8	65.4	52.6
Dec-23	7.7	21.8	73.3	54.7	49.0
Jan-24	26.7	47.0	93.9	35.8	39.1
Feb-24	91.5	105.9	89.9	60.4	30.8
Mar-24	54.0	354.5	96.4	35.6	29.8
Apr-24	47.3	240.9	58.7	44.7	32.7
May-24	0.9	25.8	5.8	23.1	40.8
Jun-24	0.0	0.6	0.1	32.6	64.6
Total:	265.8	838.5	571.1	403.1	395.8

Table 10. Subsurface runoff for treatments 1 (no envelope), 2 (synthetic envelope) and 3 (crushed rock envelope) in the year 2024-2025. Precipitation (P) from the SMHI measurement station in Sala.

2024 - 2025	Treatment 1 (mm)	Treatment 2 (mm)	Treatment 3 (mm)	P 2024-2025 (mm)	Normal P 1991-2020 (mm)
Jul-24	0.009	0.01	0.02	48.0	68.0
Aug-24	0.009	0.01	0.04	63.0	69.2
Sep-24	0.01	0.03	0.02	65.0	48.3
Oct-24	0.01	0.02	0.02	52.6	56.4
Nov-24	0.02	0.02	0.02	25.8	52.6
Dec-24	89.5	306.3	45.2	58.0	49.0
Jan-25	92.4	542.2	99.9	60.2	39.1
Feb-25	5.3	50.6	6.01	10.0	30.8
Mar-25	3.1	13.4	0.5	6.1	29.8
Apr-25	0.02	0.02	0.02	27.5	32.7
May-25	0.03	0.1	0.04	34.2	40.8
Jun-25	0.01	0.02	0.02	89.0	64.6
Total:	190.5	912.6	151.9	539.4	581.3

4.2.3 Nitrogen and phosphorus

In Figures 24 and 25, as well as Tables 11 and 12, treatment 1 (no envelope) possessed the highest concentration of total P and N compared to treatments 2 and 3, for both the years 2023-2024 and 2024-2025. Treatment 3 (crushed rock envelope) had the lowest content of total P in both years. Regarding total N concentration, treatment 2 (synthetic envelope) had the lowest concentration in both years.

The concentrations of total P and total N follow similar patterns across all treatments throughout the years (Figures 24 and 25). In 2023-2024, total P decreased from October to January but rapidly increased in February 2024, followed by a gradual decline (Figure 24). Treatments 1 and 2 had high concentrations in May and June after fertilisation. For the year 2024-2025, both total P and total N only occurred from December to March due to low subsurface runoff. Treatment 1 had slightly higher total P concentrations than treatments 2 and 3. A similar pattern was observed for total N concentration (Figure 25). The concentration of total N decreased in February 2024 (Figure 25).

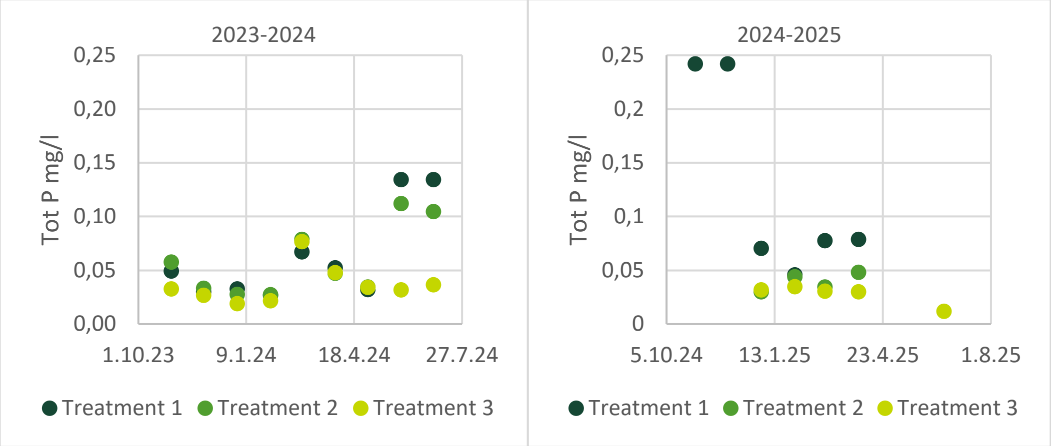


Figure 24. Total P concentration in mg/l for treatments 1, 2 and 3 for year 2023-2024 (left) and year 2024-2025 (right).

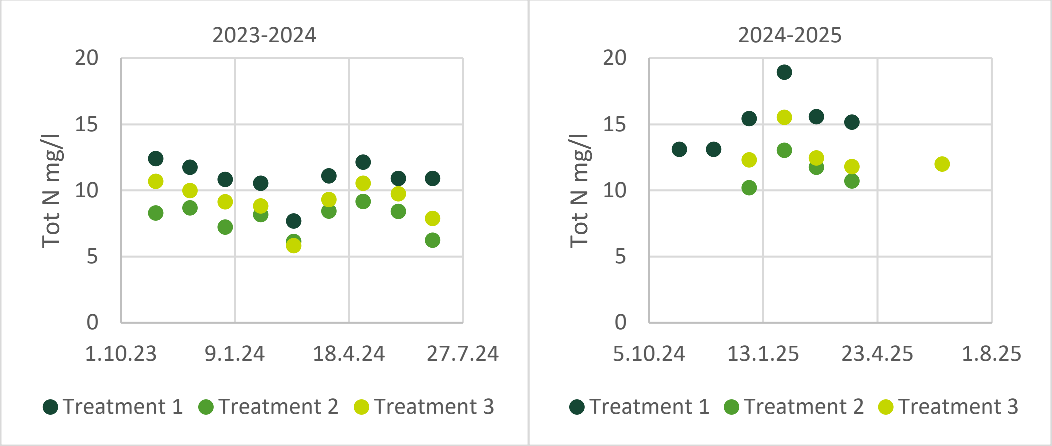


Figure 25. Total N concentration in mg/l for treatments 1, 2 and 3 for the years 2023-2024 (left) and 2024-2025 (right).

Table 11. Total P and total N concentrations in mg/l for treatments 1, 2 and 3 for each month in the year 2023-2024 and the total mean for the whole year.

	Total P concentration (mg/l)			**Total N concentration (mg/l)**		
Month	**Treatment 1**	**Treatment 2**	**Treatment 3**	**Treatment 1**	**Treatment 2**	**Treatment 3**
Oct-23	0.05	0.06	0.03	12.41	8.29	10.69
Nov-23	0.03	0.03	0.03	11.75	8.67	9.99
Dec-23	0.03	0.03	0.02	10.83	7.23	9.14
Jan-24	0.03	0.03	0.02	10.54	8.17	8.83
Feb-24	0.07	0.08	0.08	7.69	6.15	5.82
Mar-24	0.05	0.05	0.05	11.08	8.43	9.31
Apr-24	0.03	0.03	0.03	12.15	9.15	10.53
May-24	0.13	0.11	0.03	10.89	8.41	9.73
Jun-24	0.13	0.11	0.04	10.89	6.24	7.88
Mean:	0.06	0.05	0.03	10.91	7.86	9.10

Table 12. Total P and total N in mg/l for treatments 1, 2 and 3 for every month in the year 2024-2025 and the mean value of the total P and N, respectively, for the entire hydrological year.

	Total P concentration (mg/l)			**Total N concentration (mg/l)**		
Month	**Treatment 1**	**Treatment 2**	**Treatment 3**	**Treatment 1**	**Treatment 2**	**Treatment 3**
Oct-24	0.24			13.10		
Nov-24	0.24			13.10		
Dec-24	0.07	0.03	0.03	15.43	10.21	12.29
Jan-25	0.04	0.04	0.03	18.94	13.04	15.53
Feb-25	0.08	0.03	0.03	15.58	11.75	12.45
Mar-25	0.08	0.05	0.03	15.17	10.71	11.81
Apr-25						
May-25						
Jun-25			0.01			12.00
Mean:	0.13	0.04	0.03	15.22	11.43	12.81

An ANOVA was conducted on total P and total N concentrations (Tables 13 and 14). In 2023-2024, the number of observations was *n* = 171 and in 2024-2025, *n* = 51 for both total P and total N. For total N concentration, significant differences were observed across treatments in both years, but date-wise significance was only found in 2023-2024 (*p* = 0.00). For total P concentration, date-wise significance was only observed in 2023-2024 (*p* = 0.00), whereas no significant effects of date or treatment were detected in 2024-2025.

A Tukey HSD test was performed on total N concentration for the year 2023-2024, and significant differences were found between treatments 1 and 2. No significant differences were found in the year 2024-2025.

Table 13. Summary of ANOVA analyses on total P and total N concentrations in the subsurface runoff for the hydrological year 2023-2024, showing the: Degrees of freedom (df), Sum of squares (SS) and Mean square (MS). The F value is the mean square between groups divided by the mean square within groups. A p-value below 0.05 rejects the null hypothesis, indicating that the difference is not due to chance but is statistically significant.

Effect	**Substance**	**df**	**SS**	**MS**	**F**	***p***	**Significance**
Date	P	14	0.117	0.008	3.47	0.00	Yes
Treatment	P	2	0.001	0.001	0.475	0.62	No
Date	N	14	1799.93	128.57	14.24	0.00	Yes
Treatment	N	2	76.95	38.47	4.26	0.02	Yes

Table 14. Summary of ANOVA analyses on total P and total N concentrations in the subsurface runoff for the hydrological year 2024-2025, showing the: Degrees of freedom (df), Sum of squares (SS) and Mean square (MS). The F value is the mean square between groups divided by the mean square within groups. A p-value below 0.05 rejects the null hypothesis, indicating that the difference is not due to chance but is statistically significant.

Effect	**Substance**	**df**	**SS**	**MS**	**F**	***p***	**Significance**
Date	P	3	0.025	0.008	1.87	0.15	No
Treatment	P	2	0.022	0.010	2.38	0.10	No
Date	N	3	94.74	31.58	2.05	0.12	No
Treatment	N	2	131.76	65.88	4.28	0.02	Yes

5. Discussion

5.1 Soil inside the drainage pipes

During excavation, it was noted that the pipes in treatment 1 (no envelope) contained the most sediment (Figure 11), particularly in plot 11, however, a small amount of sediment was observed across all treatments. This contradicts hypothesis a) which predicted sediment in the pipes since the risk of sedimentation is greatest immediately after installation, before the soil has stabilised (Taylor 1973; Jonsson 1985). This has also been studied in the lab, where most of the sediment occurred within the first eight days (Byrne 2023). Thus, soil stabilisation only had a minor effect on the amount of sediment in the pipes. This could be due to the installation method, which was carried out with a subsurface drainage plough. This process is less disruptive to the soil than digging down the pipes. Another reason could be that the soil has a good structure, which prevented it from moving into the pipes and risking siltation. The high clay content in the field (25-40% clay) may also have been important because previous studies have shown that clay soils do not have the same need for an envelope material as a soil with less clay content than 25% clay (Wright & Sands 2001; Stuyt et al. 2005; Agar 2011).

The small amount of sediment found in the pipes indicates that the need for maintenance of the drainage system is minimal on clay soils. Indeed, there is no current need, for example, to flush the pipes to remove sediment. The fact that the risk of silting in the pipes decreases over time (Taylor 1973; Jonsson 1985) would further reduce the need for maintenance. To verify the presence of sediment in the pipes, it is necessary to revisit the pipes and examine sediment levels in about 10 years. It would also confirm whether the amount of sediment in the pipes is increasing or remaining at the same level. The choice of envelope material affects how much sediment accumulates in the drainage pipes. The treatment with the highest sediment accumulation in the pipes was treatment 1 (no envelope), supporting hypothesis b): pipes without an envelope will contain more sediment since nothing separates them from the surrounding soil. The result of the soil samples collected from each pipe also supports this hypothesis. The p-value of 0.0009 indicates that this is not a coincidence. This finding aligns with Bahçeci et al. (2018), who observed that on clay soil, the control group without an envelope possessed the most sediment inside the pipe. Treatment 2 had the smallest amount of sediment, which was expected. According to Ritzema et al. (2006), the lowest installation cost occurs when using a synthetic envelope.

A potential source of error in this case is that, during the excavation of treatment 1 (no envelope), soil could have entered through the perforations of the pipe despite every effort to prevent it. This could result in more soil in the pipe than what was present in the buried pipe and may explain why the pipes in treatment 1 (no envelope) contained more soil. This could also have been a problem in the lab during the pipe cleaning process for all treatments. The outside of the pipes was cleaned before they were cut open to reduce the risk of outside soil mixing with the soil on the inside. However, during cleaning, soil could still enter through the perforations in the pipes to the inside surface, even though I tried to avoid this as much as possible.

Treatment 2 contained the highest proportion of fine particles, likely due to the denser synthetic envelope. According to Jonsson (1985), particles sized 0.05-0.15 mm pose the greatest risk of clogging the pipes. Treatment 3 (crushed rock) had the highest proportion of particles in the size range 0.06-0.2 mm. Moreover, treatment 3 had the highest proportion of larger particles, which is consistent with the results from Falk (2019). The crushed rock used as an envelope in that field trial had a diameter of 4-8 mm, which is larger than the particle sizes analysed here. However, this does not exclude the possibility that there are particles smaller than 4-8 mm in the crushed rock, which could be a reason why treatment 3 contained the highest proportion of larger particles. To verify this, a test of the particle distribution of the crushed rock should have been performed. The particle distribution of the gravel in Falk (2019) showed that the gravel contained a small amount of finer material, 0.06-0.2 mm and smaller. Because of the large number of particles within the size range that risk clogging the pipes in treatment 3, the risk of that occurring is higher. At the same time, the total amount of sediment inside the pipes from treatment 3 was low. If there was a risk of clogging the pipes, the amount of sediment might have been higher.

5.2 The synthetic envelopes

The selected standard granular material for the test with the synthetic envelopes had a mesh size of 60, corresponding to a particle size of 0.250 mm. The measured average particle size was 0.381 mm, which is larger than the expected 0.250 mm. The synthetic envelope should have stopped 90% of all particles larger than 450 microns (0.450 mm), according to the manufacturer (MST 2025). The test of the opening size showed that 90% of the material that passed through the envelope was smaller than 0.4 mm. This corresponds to the information from the manufacturer. One possible factor that may have influenced the result is the handling of the envelope material. When the envelopes were cut from the pipe, they might have been dragged out or mistreated. Additionally, some envelopes exhibited a very uneven thickness. Another aspect that could have caused this is that when the test started, and the envelope was shaking, the granular material aggregated to a certain extent.

The soil passing through the dug-up envelope from the field predominantly contained fine particles measuring 0.0002-0.002 mm and 0.002-0.006 mm. These did not pose a risk of clogging the pipes. This is in line with the result that the soil from inside the pipes from treatment 2 (synthetic envelope) contained very little sediment and had the highest proportion of fine particles in the 0.0002-0.002 mm size range. This is consistent with the opening size from the test of the unused envelopes, $O_{90} = 0.4$ mm, and the manufacturer's information that $O_{90} = 0.45$ mm.

A large portion, 6.69%, of the soil in the envelope disappeared during the experiment. This was likely small particles, colloids, which may have become trapped on the filter paper during the filtration of the water from the test that passed through the envelope.

5.3 Turbidity

In hypothesis c) it was assumed that turbidity would be higher in the pipes without an envelope due to increased sediment loads compared with other treatments. Since treatment 1 (no envelope) contained more sediment, the hypothesis predicted higher turbidity in treatment 1. However, the highest average turbidity was found in treatment 2, and the ANOVA analysis showed that treatment 2 had a very high variance, which may be due to some extreme values in this treatment. Given these extreme variations, there may be no significant differences between the treatments. This may be due to issues with the measurement.

The results showed a very strong correlation between turbidity and suspended material, consistent with Sahoo & Anandhi (2023), who stated that suspended material and turbidity are strongly correlated. The results also showed a strong correlation between turbidity and total P, and between suspended material and total P. Notably, Fölster & Rönnback (2015) demonstrated that turbidity can indicate the amount of total P in the water due to insoluble particles.

5.4 Subsurface runoff

The measurement of subsurface runoff in plot 11 did not work as it should have, so the values of this plot (treatment 1, no envelope) were not included in the results, which may have potentially affected the results of treatment 1 (no envelope).

During the hydrological year 2023-2024, treatment 2 exhibited the highest total subsurface runoff, and treatment 1 had the lowest subsurface runoff. In March 2024, treatment 2 had the highest subsurface runoff. The highest subsurface runoff occurred in February-April for all treatments. Meanwhile, the highest precipitation occurred in October-December and February. One reason the subsurface runoff occurred in February-April rather than in October-December, when precipitation was highest, could be due to soil frost during the winter.

The annual precipitation very minorly differed from the normal levels observed between 1991 to 2020. In 2024-2025, the subsurface runoff was the greatest during August-September, December-January and June; precipitation was also the highest during these periods. The other months had almost no subsurface runoff, while the precipitation varied between 6 and 52 mm.

Over both hydrological years, treatment 2 had almost double the subsurface runoff (R = 832 mm and 912 mm) compared with the precipitation (P = 403 mm and 539 mm). This may suggest that an envelope enhances permeability around the pipe. However, a simple water balance shows that the numbers do not match. It cannot be that more water leaves the system than enters it. In treatments 1 and 3, the subsurface runoff is reasonably relative to the precipitation. Among the plots in treatment 2, no individual value can be seen to have increased the average subsurface runoff. One reason for the high subsurface runoff in treatment 2 could be linked to a fault with the measuring equipment, as no other data for treatment 2, such as sediment, N and P, have shown similar anomalies. Another possibility is that groundwater entered the pipes or that the old tile drainage system affected the new drainage system. If that was the case, the other treatments would also show higher subsurface runoff. However, treatments 1 and 3 had very low subsurface runoff during 2024-2025, which may be due to the low precipitation during the winter of 2024-2025.

5.5 Nitrogen and phosphorus concentrations

This study focuses on the concentrations of N and P in drainage water as opposed to their leaching. These concentrations can serve as indicators of water quality. To accurately assess leaching, it is necessary to include runoff in the calculation, as leaching depends on both concentration and flow. Low concentrations combined with high runoff can result in high leaching, whereas high concentrations with low runoff can lead to low leaching. Because of the uncertainties regarding the accuracy of the subsurface runoff measurements, specifically the anomalous flow values in certain treatments, total leaching calculations were considered potentially unreliable. Therefore, this study prioritises nutrient concentrations to ensure a more accurate evaluation of water quality.

The concentration of total N varies between approximately 5 and 18 mg/l. For the region where the experiment is located, the area-weighted average value concerning soil type and crop distribution for total N leaching is 4.3 mg N/l. The average in Sweden is 6.3 mg total N/l (Johnsson et al. 2023). The average values for total N in this field trial are higher than normal. However, it is important to note that Jokinen et al. (2024) and Wesström & Joel (2024) found that the concentration of total N was greater in newly installed drainage systems, which could explain the higher values. This shows how important it is that the experiment continues to see if these levels decrease over time.

The results clearly showed that treatment 1 (no envelope) had the highest concentration of total N in both hydrological years. These findings partly agree with hypothesis d) which suggests that increased sediment and turbidity in pipes without an envelope lead to higher concentrations of nitrogen and phosphorus in this treatment. There was no significance for total P concentration for either treatment or date, while there were significant differences for total N concentration between treatments for both years. N is more soluble in water than P, which is bound to particles. The task of the envelope is to increase permeability so that the water is directed into the pipe and then away from the field. Thus, it is the water that the drainage system is targeting, not the particles. Since the amount of sediment was generally low in all pipes, this could be a reason why the amount of total N concentration was higher than the total P concentration.

The significant difference in total N concentration in drainage water was found between treatments 1 (no envelope) and 2 (synthetic envelope). The use of a synthetic envelope reduces the concentration of total N in drainage water. No significant difference was found between treatments 1 and 3 (crushed rock), indicating that a crushed rock envelope does not reduce the total N concentration compared to no envelope.

The year 2023-2024 showed significance for the date for both total P and total N concentrations, while in 2024-2025, there was no significance. This is likely based on the fact that the highest subsurface runoff occurred during December-February, while in the other months, there was essentially no runoff. The precipitation during the year compares quite well with the normal precipitation from 1991-2020, but the total annual subsurface runoff was higher during 2023-2024. It may also be because the number of observations, n, was smaller in 2024-2025 (n=51) than in 2023-2024 (n=171) due to a smaller amount of subsurface runoff.

Using a drain envelope can therefore reduce the concentration of N in the drainage water. The question is whether to omit an envelope to lower drainage costs or to prioritise environmental concerns by reducing N levels in our watercourses with an envelope. Increased precipitation due to climate change is increasing the risk of nutrient leaching (Rashmi et al. 2017). An envelope can reduce this risk, which is beneficial for both the environment and adaptation to the future climate. Thus, the use of an envelope could be a viable strategy to reduce nitrogen concentrations in drainage water and thereby reduce nitrogen leaching in drainage. However, more research on this subject is needed to confirm this.

6. Conclusion

This study examined how various drainage envelope materials in clay soils affect sediment accumulation, subsurface runoff, turbidity and nitrogen and phosphorus concentrations. Furthermore, it sought to provide insights into whether using an envelope can help to reduce sediment accumulation and nutrient leaching compared with drainage pipes without an envelope.

All envelopes had minimal sediment, suggesting that pipe flushing needs are low in clay soils. This also improves the drainage system's durability. Although sediment levels were low, no-envelope material led to the highest amount of sediment inside the pipes ($p = 0.0009$). However, it should be noted that the risk of soil entering the pipes through the perforations during excavation and handling was higher for the no-envelope treatment, which may have influenced the measured sediment amounts. Despite this potential source of error, the findings indicate that the type of envelope material chosen influences sediment accumulation in drainage pipes. Consequently, using an envelope can help to mitigate the risk of sedimentation within these pipes.

It is difficult to determine whether an envelope material affects turbidity because no statistically significant differences in the turbidity were found. The difference in N concentration between the use of no envelope and the use of a synthetic envelope ($p < 0.02$), indicates that the use of an envelope might be a measure to reduce the concentration of N.

To verify the current minimum sediment quantity in the pipes and the concentrations of total P and N, a similar long-term experiment should be established on clay soil, or a follow-up visit to this field trial should be performed within ten years. Since the field trial has only been conducted for two years and the risk of sedimentation is greatest immediately after installation and decreases over time, long-term monitoring is essential to verify the durability of these findings for both sedimentation and nutrients. An assessment should also be carried out to determine whether the levels of N and P concentrations decrease when an envelope is used on soils aside from clay soils.

Using a drain envelope can reduce the concentration of N in drainage water but increases drainage costs. The loss of N can also lead to additional costs when nitrogen fertiliser must be reapplied to maintain crop yield. Sediment levels were low across treatments, minimising pipe maintenance needs regardless of envelope use. There seems to be a trade-off between saving costs by omitting the envelope and protecting the environment by reducing N levels in our watercourses using an envelope. Increased precipitation due to climate change is increasing the risk of nutrient leaching. The use of an envelope could therefore be a strategy to limit nitrogen leaching from drainage, but more research is needed to confirm these findings.

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Populärvetenskaplig sammanfattning

Med klimatförändringarna kommer nederbörden att öka och då är det viktigt att vi har väldränerade åkrar som så att vi kan producera mat. En väldränerad jord ger grödan optimala odlingsförhållanden och ökar skörden. Inom växtodlingen idag är det många lantbrukare som anlägger nya dräneringssystem på sina fält för att förbättra odlingsförhållandena och öka avkastningen. När en lantbrukare ska anlägga en dränering, behövs ett val göras om dräneringsfilter som ska läggas runt dräneringsröret. Det vanligaste materialet för dräneringsfilter är grus eller bergkross, men syntetiska material som lindas runt dräneringsröret blir allt vanligare. Dessa material utgör en stor del av anläggningskostnaden för dräneringen. Dräneringsfiltrets viktigaste uppgifter är att öka genomsläppligheten runt röret för att vatten lättare ska ledas in i röret samt hindra partiklar från den omgivande jorden att tränga in i röret och ansamlas där. Sedimentansamling i rören hindrar flödet och skapar ett större behov av underhåll av dräneringssystemet. Samtidigt riskerar växtnäring i form av kväve och fosfor att läcka ut via dräneringsvattnet till våra vattendrag och sjöar.

Ett fältförsök anlades 2023 i Mellansverige för att undersöka dräneringssystem på lerjord med tre olika dräneringsfilter: inget filter, syntetiskt filter samt bergkross som dräneringsfilter. Detta för att undersöka sedimentationen i rören och vattenkvaliteten i form av avrinning, grumlighet och näringsläckage av kväve och fosfor för att se om det blir någon skillnad beroende på vilket dräneringsfilter som används. I fältförsöket grävdes en bit av dräneringsrören upp för att kunna undersöka mängden sediment i rören. Provtagning av dräneringsvatten skedde kontinuerligt från försöket. Data som samlades in sammanställdes och statistiska analyser genomfördes för att se likheter och skillnader mellan olika dräneringsfilter.

Resultaten visade en låg förekomst av sediment i alla rör, men rören utan dräneringsfilter innehöll mest sediment. Valet att inte använda ett dräneringsfilter kan alltså öka mängden sediment i rören. En felkälla här är att jord kan ha kommit in i rören under hanteringen av rören, vilket kan ha bidragit till mer sediment i rören utan ett dräneringsfilter. Den låga förekomsten av sediment i alla rör visar på lång hållbarhet och minskat behov av underhåll av dräneringen på lerjord, särskilt vid användning av dräneringsfilter. När inget dräneringsfilter används ökar koncentrationen av kväve i dräneringsvattnet. Det gick inte att se en sådan minskning för fosfor. Med tanke på våra miljömål, där ett mål är att minska övergödning, kan valet av dräneringsfilter vara en strategi för att minska kväveläckaget och skydda miljön, men mer forskning behövs för att bekräfta dessa resultat.

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