TKI - report Meegroeidijk Lauwersoog

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Summary

This report presents the outcomes of the TKI project – Meegroeidijk Lauwersoog, focusing on the development and testing of the Growing Dike Concept (GDC). This report describes the outcomes of the TKI project – Meegroeidijk Lauwersoog. The GDC, using thin layers of dredged material to reinforce dikes, had before this TKI project only been developed on paper, starting in 2019. This was done partly through a conceptual feasibility study, but never tested on small-scale experiments or in a field setting. Within this TKI project the first implementation of the GDC was tested and analysed in small-scale experiments at Deltares (Delft) and in a field pilot at the dike east of Lauwersoog.

The TKI project is an innovative collaborative project together with partners from the waterboard Noorderzijlvest, Wageningen Marine Research, HAN University of Applied Science, Klaei BV, Havenbedrijf Lauwersoog and Deltares (project activities coordinator).

The GDC involves the reinforcement of flood defences by periodically adding locally dredged material, aligning with the principles of 'Slow Building', 'Building with Nature' and 'Beneficial Use of Sediment'. This approach has the potential to enhance long-term flood defence reinforcements by repurposing locally dredged sediment as a valuable building material instead of being removed from the system as undesirable material. In addition, this approach has potentially an impact on reducing Green House Gas (GHG) emissions compared to conventional reinforcements.

The GDC offers a promising integrated solution to major challenges like sea level rise and subsidence, improving water safety in coastal and river areas. In addition, the local re-use of raw material, such as sediment from ports and waterways dredging, could potentially reduce the GHG impact of dike construction and maintenance. The gradual application of sediment may expand the lifespan of flood defences, delaying or even preventing costly maintenance while mitigating flood risks. In addition, the direct use of local sediment eliminates the need for maturation in specific depots, streamlining the connection between dredging and dike maintenance.

In this TKI project, the GDC was implemented, tested, and evaluated for the first time, marking a significant milestone in transitioning to circular sediment reuse and promoting sustainable flood risk management.

The main challenges the GDC aims at addressing in an integrated way are:

- Dike maintenance, sea level rise and subsidence
- Reduction of GHG emissions
- Circular reuse of dredged sediment

The key research questions driving this project and addressing these challenges are:

- What are the most effective application methods for different test locations?
- How can we minimize environmental impacts during and after application (landscape and smell)?
- What is the most suitable material for different test locations? What is the final height increase of the dike after consolidation and drying of the applied sediment, and how long does this process take?
- How quickly can dike vegetation recover, and how does this depend on sediment characteristics, layer thickness, initial vegetation composition and height, and seed availability within the sediment?

- Does the application of sediment mixed with fresh, and saltwater affect the chemical parameters of the topsoil layer of the dike?

Techniques and methods

To test the feasibility of the GDC and address the research questions, comprehensive research involving desk studies, laboratory experiments, field trials and numerical model testing was conducted.

The small-scale experiment on the Deltares campus focused on the effects of sediment layer thickness and initial vegetation length. Two scenarios with different sediment layer thicknesses and vegetation lengths were tested, monitoring key sediment properties such as bulk density, water content, and ion concentration during the first month. Additionally, the shear strength of the top layer was also measured.

In parallel, a qualitative application experiment explored the most efficient way for GDC implementation on a real scenario (i.e., the same dike of the pilot at Lauwersoog). This involved testing the stages of collection, mixing, transportation, and application of dredged sediment to develop a “Spraying protocol”. The latter delineates a set of instructions for achieving uniform layer thickness across the dike slope specific for the situation at the dike of Lauwersoog.

Within the pilot, the GDC was tested on a real-scale dike at Lauwersoog, following the outcomes of the previous small-scale and application experiment. Seven treatments were tested in duplicate, varying in sediment layer thickness, mixing with fresh or saltwater, and seed addition. Sediment layer thickness evolution was monitored using rulers, Sediment Erosion Bars (SEBs), and a drone. Vegetation regrowth after the application of the sediment layer was evaluated by assessing species cover and estimating growth within permanent quadrants (PQs). In addition, chemical analyses investigated the potential ion runoff and leaching, with subsequent variation of chemical composition of the dike topsoil, while GHG fluxes were measured before, immediately after, and three months post-application using a portable in situ gas monitoring system.

The modelling approach was conducted in parallel with and after the application experiment and the pilot. The results obtained during the pilot are used to get insights into the value of the modelling approach. Additionally, while trialling various application methods, considering fluid mechanics may help identify the most efficient application method.

Results

The combined results of the small-scale and application experiment, along with the pilot, provided an initial overview of the feasibility and applicability of the GDC.

The water content of the applied sediment decreased from approximately 65% to 25% in the first week, affecting the sediment layer thickness, which compacted by approximately 65% during the same period due to dewatering and consolidation. After three months, there was no statistically significant change in layer thickness.

Chemical analyses showed runoff and leaching of ions, such as bromide, chloride, sodium, ammonium, and nitrate, into the soil. A slight, non-significant increase in organic matter was observed in the soil, likely due to biomass growth through the sediment layer. Phosphate and sulphate concentrations increased in both soil and sediment, the former likely due to mineralization triggered by the change in chemical composition post-application of the sediment. Conversely, the increase in sulphate is probably the result of drying of the marine sediment.

As the sediment dried, it hardened and cracked, allowing vegetation to grow through. After three months, vegetation cover, which was mostly composed by grass, ranged between 40% and 75%, and exceeded 90% after nine months. The addition of seeds to the sediment mixture slightly accelerated vegetation recovery, depending on the plant’s species in the seed mix. Vegetation recovery was unaffected by sediment dilution and layer thickness, but it may be influenced by factors like initial vegetation composition, dike composition (i.e.,slope, angle, height), and weather conditions.

The characteristics of the material, the spraying method, and the dike's geometry (excluding the vegetation) served as input parameters for the numerical model used to estimate the theoretical thickness. The calculation resulted in a layer thickness of approximately 2 cm.

GHG flux analyses from the dike surface showed that the sediment application initially halted vegetation uptake processes, leading to CO_2 and CH_4 emissions. After three months, as vegetation partially recovered and sediment organic matter oxidized, GHG fluxes decreased.

This project, composed by the small-scale and application experiment, the pilot at Lauwersoog and the numerical modelling, enabled us to investigate the feasibility of implementing the GDC for flood defence reinforcement.

The application experiment provided a qualitative overview of all the GDC phases, from dredging and mixing the sediment at the harbour to its transportation and application on the dike. This experiment was crucial for developing a "Spraying Protocol", which served as input for the pilot.

The small-scale experiment and the pilot, enabled to quantitively test and evaluate the GDC implementation at two different scales. During both experiments, the principal physical and chemical properties of the sediment were measured and monitored to study the evolution of the sediment layer over time. The impact on vegetation was also assessed, focusing on the differences between the two sediment treatments tested. The Lauwersoog pilot provided the first test of the GDC, highlighting key parameters and issues to address to effectively implement this approach.

By using the numerical models one can get insight in expected layer thickness development when the material is sprayed considering the specific inputs of dike characteristics and applied sediment properties.

This first feasibility and implementation tests of the GDC provided many practical insights and lessons. However, additional research is needed on several points: ensuring homogeneous sediment layers with specific thickness, evaluating the timescale and impact of ion infiltration into the soil with following variation of characteristics, assessing the resistance of the applied sediment layer and its adhesion to the dike.

Contents

1 Introduction

This report describes the results of the TKI project – Meegroeidijk Lauwersoog. The Growing Dike Concept (GDC), using thin layers of dredged material to reinforce dikes, had before this TKI project only been developed on paper. This was done partly through a conceptual feasibility study, but never tested on small-scale experiments or in a field setting. Within this TKI project the first implementation of the GDC was tested and analysed. The results from the project within this TKI phase are important in the overall Growing Dike plans for the coming years, as it represents a GO/NO GO moment within the KIA-proposal for HWBP-STOWA.

The report starts with an introduction providing the background and the history of the GDC, the phased approach, the relevance of the research, other initiatives and developments, the goals of the report and the reading guide.

1.1 Background

The GDC, involving the reinforcement of flood defences by adding thin layers of dredged material, holds the potential to positively impact the water safety of these defences. The GDC entails the periodic application of thin layers of locally dredged material on nearby flood defences, typically ranging from once a year to once every five years, depending on the specific circumstances. Strengthening flood defences with locally sourced material has a reduced impact compared to conventional reinforcements, making dredged sediment a valuable building material rather than being dredged and then removed from the system as a waste material.

This concept presents a promising integrated solution for the transition to circular (re)use of sediment, fostering more sustainable flood risk management, and reducing of GreenHouse Gas (GHG) emissions in the dike construction chain. Furthermore, this solution provides the opportunity for synergies between dredging and dike maintenance activities, resulting in cost savings through a work-with-work approach.

1.2 Consortium

This innovative collaboration project was executed with the waterboard Noorderzijlvest, Wageningen Marine Research, HAN University of Applied Sciences, Klaei BV, Havenbedrijf Lauwersoog and coordinated by Deltares.

1.3 Phased approach

As shown in Figure 1.1, the Growing Dike Concept has been setup in a phased approach which gave the different contributing consortia the opportunity to adapt when needed. The GDC was firstly discussed and developed in 2020 during EcoShape workshops and within the Flood Defences Program Committee (PCWK). The Phase 1 (2020-2021) of the GDC project consisted of a one-year collaboration with several waterboards, knowledge institutes and commercial partners, and it concluded with an 'Implementation and Scale-up plan' (see Appendix 10A, with a summary of the results of the previous phases[1]). This plan provided a comprehensive overview of the initial developments of the GDC, including the business case and circularity aspects. Additionally, it delivered a well-supported framework delineating the

[1] Deltares report 11205748-002-BGS-0004_v0.1-Meegroeidijk uitvoerings- en opschalingsplan

necessary approach for conducting research and development to determine the feasibility of the Growing Dike implementation. Phase 2 (2021- 2024) consisted of business cases for the waterboard Brabantse Delta[2] and Hoogheemraadschap Rijnland [3]and preparations were started for a TKI project, which resulted in the TKI project – Meegroeidijk Lauwersoog.

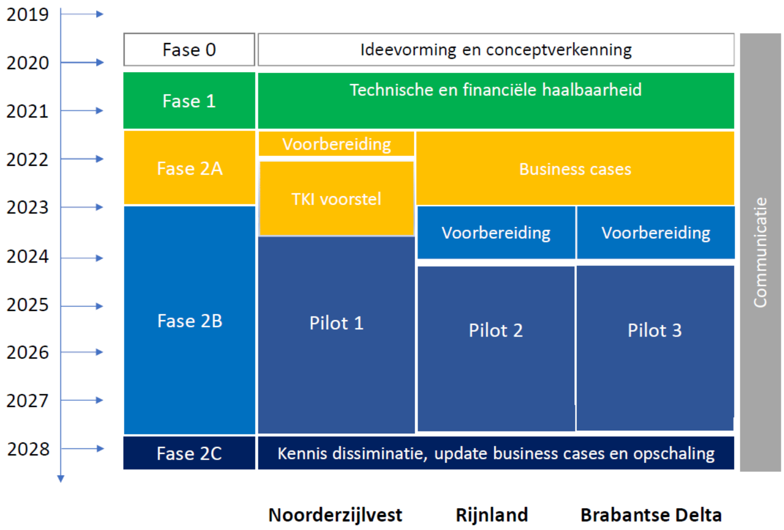

Figure 1.1: Overview of the various phases of the GDC program. Phase 1 and 2A have been completed. The TKI project for waterboard Noorderzijlvest will conclude in 2024. The follow up FASE 2B is still in the proposal phase.

1.4 Relevance of the research

The challenges that the Growing Dike addresses are listed and briefly explained below:

- **Sea level rise, soil subsidence, higher discharge and stricter standards** are major challenges for the safety of coastal and river areas (both main water systems and at regional scale). The central questions revolve around how to ensure flood protection and, at the same time, affordability. It is evident that sea levels are rising and will continue to rise. The focus is, therefore, on the longevity of traditional dike reinforcements in terms of affordability and design lifespan.
- **Greenhouse gas** emissions are the primary contributor to and accelerator for global warming. The challenge is to mitigate our CO_2 (as well as methane and nitrous oxide) impact while simultaneously developing the economy and enhancing social welfare, aligning with the commitments outlined in the Paris agreement. This commitment is further delineated in several European Union (EU) directives and at national level, as well as in the Knowledge & Innovation Agendas of the various Dutch Top Sectors.
- **Raw materials** are scarce and are consumed on a large scale. This also applies to soil: for example, much more clay is still being extracted than is naturally deposited in the Dutch river area. The local reuse and re-purpose of raw materials, such as sediment from ports and waterways dredging, can solve different issues and generate multiple benefits. The main question is how we can safely and affordably reuse these natural resources.

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[2] RHDHV report BI2206-RHD-ZZ-XX-RP-Z-0001 – Business case op maat Waterschap Brabantse Delta
[3] RHDHV report BI2206-RHD-ZZ-XX-RP-Z-0001- Business case op meat Rijnland

With the Growing Dike Concept, we seek innovations that address these challenges with an integral approach, combining and aligning them. Specifically, it addresses the three mentioned challenges through the gradual, long-term (re)use of small volumes of local dredged sediment directly for dike reinforcement, eliminating the need for maturation in depots. As a result, the Growing Dike may offer an integral solution for the transition to a circular economy, more sustainable and affordable water safety, as well as reduction of GHG emissions. Furthermore, as already mentioned, this solution provides the opportunity to generate work-with-work by connecting dredging and dike maintenance activities, resulting in both efficiency gains and cost savings.
To test the feasibility of the GDC and to address the challenges detailed above, comprehensive research is required. The latter involves field trials, desk studies, laboratory experiments, and model testing. After initial implementation and discussion of the results with the involved stakeholders, this innovative concept will be ready for scaling up to other coastal and river environments in the Netherlands and possibly also abroad.

1.5 Other initiatives and developments

This project aligns with the Multi-Year Mission-Driven Innovation Programs (MMIP), specifically MMIP F1, which focuses on the sustainability and cost control of water management implementation projects. More specifically, it emphasizes the circular (re)use of raw materials derived from dredging activities, aiming towards achieving a CO_2-neutral implementation of water management projects, considering both equipment and materials. The project also focuses on the integration of measures into the natural socio-economic system, the multifunctional use of space, and the implementation of natural solutions (i.e., Building with Nature). This project is also linked with MMIP F2, addressing the adaptation to accelerated sea level rise and increasing weather extremes. It particularly contributes to developing adaptation strategies and solutions that ensure the continued functionality of the Dutch delta amidst sea level rise and climate change challenges. To a lesser extent, this project also ties in with mission B, climate neutral agriculture and food production, of the Knowledge and Innovation Agenda Agriculture, Water, Food (KIA LWV). Some initiatives are described in the attached appendix 10B. Furthermore, it also contributes to the Knowledge and Innovation Agenda - Circular Economy.

1.6 Goals of the report

This report has two main objectives:

1. To present the development and testing of the Growing Dike Concept.
   In further detail, this involves:
   a) Developing and testing an innovative method for the application of thin layers of fresh dredged sediment onto a dike
   b) Measuring and documenting the development of knowledge about sediment and grass properties, as well as carbon emissions resulting from sediment oxidation
   c) Formulating innovative relationships/(analytical) models to calculate the erosion resistance of maturated sediment and the carbon cycle encompassing both the material and the equipment.

And

2. To provide recommendations, based on the project’s outcomes, for the subsequent phase of the KIA HWBP-STOWA proposal.

1.7 Reading Guide

Chapter 3 provides an overview of the TKI project, offering insights into the consortium, selected locations, small scale experiment, application experiment, and the pilot at Lauwersoog.
Chapter 4 presents the small-scale field experiment, investigating the maturation of dredged sediment for various layer thicknesses on a slope and its impact on vegetation.
Chapter 5 focuses on the application field experiment, investigating different spraying methods to enhance our understanding of how to effectively implement the GDC in practice.
Chapter 6 focuses on the pilot itself, detailing the implementation of the GDC on an actual dike near Lauwersoog within the Noorderzijlvest waterboard.
Chapter 7 presents the modelling approach which has been applied to quantitatively assess the theoretical layer thickness achievable on the slope.
Chapter 8 reports the conclusions which serve as input for the syntheses and the subsequent steps and follow-up actions outlined in Chapter 9.

2 The Growing Dike Concept

2.1 What is the Growing Dike Concept?

The main idea of the GDC involves utilizing local dredged material for the long-term reinforcement of flood defences illustrated in Figure 2.1. This results in the gradual growth of the flood defence, assuring water safety amid sea level rise and/or subsidence. The material (re)use is circular, forming a closed chain and leading to a reduction in CO_2 and potentially other greenhouse gas emissions from the maturation of the sediment. Implementing the GDC does not entail an immediate, exclusive reinforcement of a flood defence. Due to the gradual nature of this defence reinforcement, significant measures can be postponed or kept relatively limited.

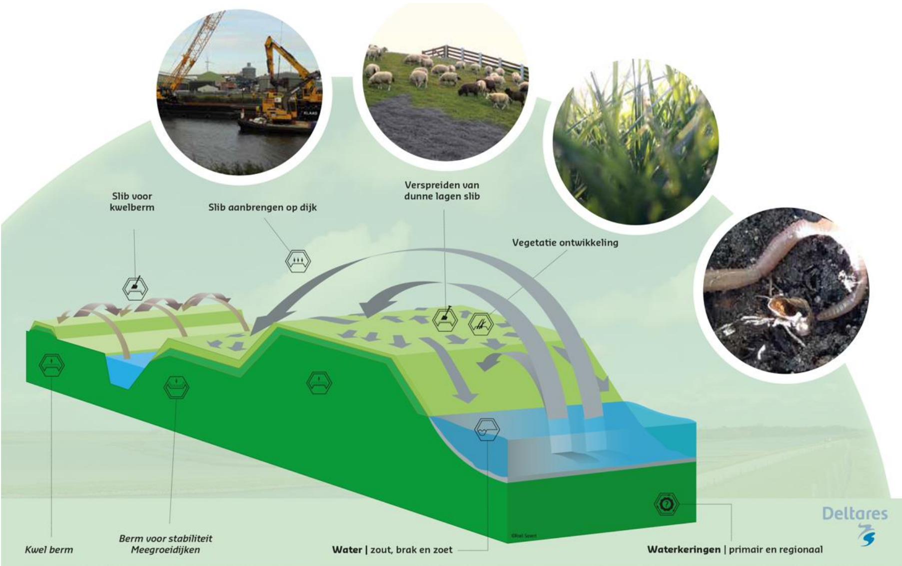


Figure 2.1: Schematic overview of the GDC, illustrating the dike, anti-piping berm, and seepage dike all progressively growing through regular application of thin layers of dredged material, which matures into clay directly on the dike.

The GDC links both management and maintenance of dikes, aligning them with the strategic objectives of waterboards, outlined below:

- Re-purposing of dredged sediment, with the reuse of class 1 and 2 dredged materials.
- Application of dredged material to primary and secondary flood defences, both in fresh and saltwater environments. This involves applying the material directly on the dike and constructing a piping berm.
- Cost-efficient maintenance works and contribution to the major dike improvement task for 2050.
- Extension of the dike’s lifespan to prevent expensive repairs and mitigate flooding-related risks. This objective aligns with the broader transformation toward climate adaptation in dike management and maintenance.
- Nature development and natural fertilization.
- Reduction of GHG emissions across the entire dike construction and maintenance chain compared to traditional dike reinforcement processes.

2.2 Application through different methods

Dredged material can be applied on the dike through various methods, briefly explained below and illustrated in Figure 2.2:

- The traditional methods, entailing the use of an excavator from a pontoon. The advantage of this approach lies in its widespread applicability due to the availability of the resources. This method can be employed when the waterway is sufficiently wide. If the waterbody or waterway lacks the necessary width, alternative methods for applying the material are available.
- The more experimental sediment spray method, while requiring specialized equipment, is expected to result in less CO_2 emissions. Consequently, this method is more attractive for potential further scale-up. Additionally, it is suitable for barriers if the crest is sufficiently wide and can withstand the load in relation to the equipment used.

The GDC has potential applications across different scenarios (refers also to Figure 2.1 and Figure 2.2):

1. At primary flood defences: This method has not been implemented so far, mainly due to uncertainties surrounding the primary function of these dikes in ensuring water safety.
2. For regional flood defences: in practice, this concept is implicitly employed in the maintenance of ditches and canals. Instead of being removed, the material is often 'put aside'. However, this practice is not intentional from a water safety perspective but rather out of habit and convenience. The dredged freshwater material typically contains a substantial amount of organic material, similar to the subsoil on which the dike is situated. Nevertheless, there is limited understanding of the relationship between the properties of the dredged material and its impact on water safety.
3. During the construction or maintenance of an anti-piping berm.
4. During the construction or maintenance of a anti seeping dike.

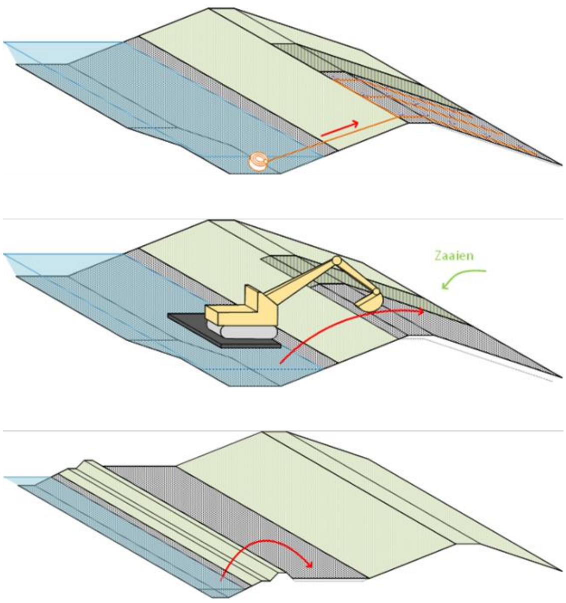


Figure 2.2: Schematic overview of different application method of sediment. Spraying method (top) and mechanical application (middle) to the dike, and (re)use of material for piping berm or salt marsh dike (bottom).

2.3 Effects of Growing dikes on the water safety of flood defences

To implement the GDC as a reinforcement measure for flood defences, it is crucial to investigate and quantify the impact of the concept on the water safety of flood defences. The water safety provided by a dike is expressed by the probability of flooding and collapsing.

The collapse of a dike can result from various ‘failure mechanisms’ which consist in a sequence of different events that jointly lead to the failure of the barrier. While the concept of failure mechanisms remains fundamentally the same for regional defences, a failure probability approach is not employed. Instead, an exceedance frequency and derived safety standards are utilized, with regional defences following a semi-probabilistic approach and primary defences adhering to a probabilistic one.

Failure mechanisms are often grouped around a similar initial mechanism, such as the failure of a dike’s vegetation layer. Subsequently, various combinations of subsequent mechanisms, also called ‘failure paths’, are possible and that can lead to failure. When assessing the contribution of a failure mechanism to the probability of flooding, the probability of the dominant failure path (i.e., the failure path with the greatest probability of occurrence) is typically considered. The probability of flooding of a dike section is then determined by a combination of various failure probabilities resulting from all potential failure mechanisms.

When determining the influence of the GDC concept on water safety, it is essential to identify its influence on the most relevant failure mechanisms. While some of these influences can be adequately estimated, there are gaps in available knowledge in other areas, making it challenging to interpret the effect of the GDC concept on water safety. In addition to its direct influence on failure mechanism, the concept can also be utilized in anticipation of a reinforcement related to another failure mechanism. Understanding the strengthening the barrier for this purpose requires a less intense measure for the failure mechanism for which the barrier already has been strengthened using the Growing Dike Concept

2.3.1 The height of the dike

Implementing the GDC concept is expected to result in an increase in the dike’s height (the material is also applied to the crest) and can also be implemented in areas as a compensation for areas with soil subsidence. This decreases the chance of failure, as this chance decreases with a higher crown. However, there is still significant uncertainty regarding the expected height increase. Some of the applied material may wash away, and the remaining sediment layer(s) will also settle and/ or oxidize. These processes partly depend on the composition of the applied material, the thickness of the layers, and the frequency of their application.

Distinction failure mechanisms are identified, including:

- The occurrence of dike erosion (failure of the grass covering of a dike, resulting in erosion of the dike body). This is often categorized into:
  - Failure of the grass covering on the outer slope.
  - Failure of the grass covering on the crown or inner slope.
  - The occurrence of micro-instability, causing part of the cladding to shear.
- Failure due to the occurrence of piping.
- Failure due to the occurrence of macro-instability or the slip of the top layer (vegetation)

2.3.2 Dike erosion

This failure mechanism is caused by the initial failure of the covering layer of a dike. A distinction is often made between the failure of a vegetation layer on the outside of a dike (due to the impact of waves or rising waves over the slope, known as GEBU) and the failure of a grass vegetation layer on the crown or inner slope due to water running over the dike or waves crashing over the crest and running down the inner slope (GEKB). This involves erosion resulting from damage to the top of the vegetation layer, and it is expected that this aspect can be mitigated by applying the GDC concept.

Micro-instability may also cause the vegetation layer and possibly part of the dike body to slide, initiating an erosion process in which the underlying (often clay) layer erodes.

Important properties influencing the speed and probability of occurrence of this process include:

- The strength of the top layer's vegetation, indicating its resistance wave impacts and its ability to withstand water running along the slope.
- The height of the dike, determining the extent to which water can wash over it during high water levels and/or waves.
- The erosion resistance of the clay layer beneath the grass cover.
- The cohesion or adhesion of the clay layers beneath the covering.
- The phreatic groundwater level within the dike.

Height of the dike
Knowledge gap: There is limited knowledge about the main characteristics of dredged material, including its composition, and its direct impact on the thickness and frequency of application for achieving the final dike height after settling and/or oxidation of various layers of dredged material. Furthermore the composition of dredged sediment varies locally and seasonally and literature shows that small changes in composition affect the mechanical behaviour of dredged sediment (e.g. Jacobs, 2011; Barciela-Rial et al., 2020; Barciela-Rial et al, 2022;) Understanding these characteristics and their relationship with the eventual applied elevation, subsidence, and/or oxidation over time is essential for accurately estimating the added strength resulting from the implementation of the GDC.

Strength of the vegetation
The strength of the vegetation covering plays a crucial role in determining how quickly a hole can develop in the top layer. This is partly influenced by factors such as the density of the grass and the degree of rooting. In calculations for assessing water safety, this is translated into a critical flow speed of the water over the top layer. If this speed is exceeded, a gap may occur. The hypothesis when applying the GDC is that grass can gets a better quality and grow through the thin layer when thin layers are applied. However, little is known about the relationship between the quality of the grass covering and the composition of the applied material, or, for example, the thickness and frequency of the applied layers. It is also unclear whether additional sowing after applying a new layer of material is necessary to maintain the strength of the grass covering.

Knowledge gap: Currently, there is limited understanding of the relationship between the quality of the grass covering and the characteristics of the applied material, including salt content, the presence of organic material, thickness, and frequency of application. This knowledge is crucial for effectively implementing the GDC to enhance water safety.
Another factor influencing the strength of the grass covering is the degree of heterogeneity and the presence of cracks in the covering. The application of layers of material is expected to influence the moisture balance of the upper clay layer of a dike, potentially positively affecting the susceptibility of the grass cover to drought.

Knowledge gap: There is still insufficient knowledge about the impact of applying thin material layers on the moisture balance and, consequently, the quality of a grass covering. Further insights into this matter could also provide information about the potential to prevent or mitigate crack formation in the dike.

Erosion resistance of the underlay(s).
After the top layer of the vegetation layer has collapsed and there is no more grass, a clay layer remains that is also erosion resistant for some time. The speed at which this layer (applied with the GDC concept) erodes has already been the subject of several studies. However, there is still little clarity about the determining clay parameters when it comes to the erosion rate, when there are several thin clay layers applied one after the other.

Knowledge gap: There is still insufficient knowledge about the erosion resistance of clay applied in multiple thin layers. This knowledge is important to properly estimate the effect of applying the GDC on water safety (and in particular the erosion process after failure of a vegetation layer).

Cohesion or adhesion of the applied sediment layers
One of the mechanisms that can cause the removal of a grass layer is the sliding of the top layer or one of the layers below it. This immediately causes a hole in the top layer and therefore a wave or current attack on the layers below it. The shear strength of the underlying clay layer (or layers) is usually a good indicator for this. After applying several thin layers of sediment with possibly varying properties, layers may have poor adhesion, which could cause this mechanism to occur more quickly.

Knowledge gap: So far there is no knowledge about the degree of adhesion and/or cohesion between two or more thin layers of sediment applied one after the other. This means that the consequences of applying the GDC with regard to shearing of a covering are difficult to estimate. To apply the concept in the context of water safety, it is therefore important to understand the degree of cohesion between the different applied layers of sediment and the relationship with the determining properties of this sludge.

2.3.3 Piping

The failure mechanism piping arises because water (together with sand particles) flows under the dike. Behind the dike the water with the sand particles rises. This creates a small channel (a ‘pipe’) under the dike and one on the inside of the dike. Once this pipe has been created, it grows rapidly until the pipe becomes so large that the dike subsides.

Important properties for whether this will occur are the composition of the subsurface (i.e. under the dike), the difference in level between the water levels on either side of the dike and the degree of closure of a possible pipe due to the presence of a clay layer with sufficient mass to prevent it from bursting.

When applying the GDC, you can choose to apply sediment in places where there is a risk of the existing clay layer cracking. This extra volume (and therefore weight) reduces the chance of cracking and therefore in many cases also the chance that piping can occur.

Although implementation of the GDC can have a positive influence on reducing the risk of piping, this does not add additional knowledge questions compared to the existing knowledge gaps. The mass (including its uncertainty) of the applied sediment can be estimated in advance and utilized with existing calculation methods for designing reinforcements or determining the probability of flooding.

2.3.4 Macro instability

Macro instability is caused by shearing of part of the dike on the outside. The mechanism can occur if the weight of material on the dike becomes heavier than the shear resistance of the material of the dike body can provide. In that case, a sliding circle is created, and part of the dike slides away.

Applying the GDC has a relatively limited influence on this failure mechanism. As with regular dike reinforcements, the positioning of the applied material is important for the weight distribution and therefore also for adjusting the chance of this mechanism occurring. In that area too, the GDC does not entail any additional knowledge gaps.

2.3.5 Summary of knowledge gaps regarding the GDC and failure mechanisms

In summary, the existing knowledge gaps are reported in Table 2.1 below.

Table 2.1: Existing knowledge gaps regarding the GDC and failure mechanisms. GEKB=Gras Erosie Kruin en Binnentalud (Grass erosion crest and inner slope), GEBU=Gras Erosie Buitentalud (Grass erosion outside slope).

Failure mechanism	Considered parameter	Knowledge gap
GEKB	Height change (Δh)	How much material is eroded and what parameters determine the rate of subsidence and/or oxidation of the applied layers?
GEKB + GEBU	Critical flow rate (U_c)	What is the relationship between the layer thickness and frequency of the application, also with any additional seeding of grass and the quality of the grass revetment?
		How is the sediment layering determined and how does it affect grass rooting, and thus erosion resistance?
	Shear strength of clay layer	What are the determining factors for the degree of cohesion of the different applied sediment layers and how do they affect the strength of the embankment against shear of the revetment or the occurrence of micro-instability?
	Moisture content of the topsoil (grass cover)	How does sediment layering affect topsoil moisture content, and can it be used to prevent or mitigate against cracking?
Piping	-	-
Macro-instability	-	-

2.4 Contribution of the Growing Dike to circularity

The Growing Dike aligns coherently with the principles of ‘Slow Building’, ‘Building with Nature’, and ‘Beneficial Use of Sediment’. Below, we provide a summary of these principles highlighting relevant examples.

Slow building

With “Slow Building” the movement of material is accomplished through gradual and long-term dredging work (Raadgever et al., 2020). This method of construction has the potential to use significantly less energy and can lead to lower visual impacts. With Slow Building, an attempt can be made to (re)connect construction operations with natural dynamic processes, such as floods, erosion and siltation, and delta formation. Additionally, “Slow Building” can in certain cases be an effective option compared to the current “fast building”, for example slowly expanding nature reserves, slowly raising, and strengthening of dikes, and slowly nourishing the coast. Finally, the total emissions can be smaller with Slow Building, especially due to the possible use of sustainable energy sources. For example, dredged material is only transported through a dredging pipeline when the wind turbine supplies sufficient energy.

Building with Nature
The concept of “Building with Nature" leverages natural processes, such as sediment transport and vegetation growth, to benefit economy, society, and the environment (https://www.ecoshape.org/en/). The ‘Space for the River’ program and the ‘Sand Motor’ are iconic Dutch examples of this. Reusing sediment can offer important benefits in terms of water safety, navigability of waterways, water quality and development of the local economy.

Reuse of sediment
In the “Living lab for MUD” (Sittoni et al., 2022), various organizations worked on five projects to develop knowledge about the sustainable (re)use of fine sediment (https://www.ecoshape.org/nl/pilots/living-lab-mud/). The ‘Kleirijperij’, the ‘Mud Engine’ and the Pilot Raisin Agricultural Land are the three most important examples for this study. In the ‘Kleirijperij’, dredged material from the port of Delfzijl and Polder Breebaart is converted into strong clay through dewatering, desalination, and oxidation. In the ‘Mud Motor’, dredged material from the port of Harlingen is placed in shallower waters along the Wadden coast of Friesland so that natural currents can transport it further to the coast and protect the latter from erosion. In the Pilot Raising Agricultural Land, dredged sediment from the Eems Harbour was used to stop oxidation of peat layer by adding dredged sediment on top. Reuse of sediment is also central to the EU project ‘SURICATES’ (https://www.nweurope.eu/projects/project-search/suricates-sediment-uses-as-resources-in-circular-and-territorial-economies/). The port of Rotterdam is the most relevant example here, where dredged sediment has been used to strengthen dikes against flooding.

2.5 Contribution of the Growing Dike to the reduction of Green House Gas emissions

The implementation of the GDC has the potential to significantly reduce greenhouse gas emissions throughout the entire dike construction and maintenance chain compared to traditional dike reinforcement processes.

Firstly, (re)using local dredged sediment leads to shorter distances between dredging and application locations. Instead of transporting new and additional building material over long distances, the GDC solely utilizes the material already present in the local system, avoiding the need to move the sediment out of the system. Additionally, the transportation of local material could be further optimized, and its GHG footprint minimized, by using pipelines powered with more sustainable energy, such as energy from wind turbine.

In addition to measuring greenhouse gas fluxes, it is crucial to determine the amount of organic material is stored in the dredged sediment and its quality (i.e., degradability). If a significant amount of easily degradable organic material is present, it can be microbiologically degraded quite quickly under the right conditions, resulting in high emissions. Therefore, monitoring soil organic matter throughout the project is essential.

2.6 Research questions

In the preliminary phase of the Implementation and Scale-up plan, together with all partners of the consortium, the main research questions surrounding the feasibility and viability of the GDC were identified. The main research questions regarding the application (and following scale-up) of the Growing Dike are summarised below.

1. **Application method**
   a. What are the most effective application methods for different test locations?
2. **Dike management and reinforcement**
   a. What are the opportunities and challenges of the GDC for the various failure mechanisms?
   b. What is a suitable management method?
   c. What is the influence on the landscape design process?
   d. What is the CO_2 footprint compared to regular (and traditional) dredging and dike improvement?
   e. How do we keep the impact on the environment (landscape and smell) as low as possible?
3. **Sediment and Vegetation**
   a. What is the most suitable material for different test locations?
   b. What is the balance between supply and demand for dredged material at test locations and during scale-up?
   c. How fast can the vegetation of the dike recover and how does this depend on:
      i. Layer thickness
      ii. Initial vegetation composition and height
      iii. Salinity of the dredged sediment
      iv. Availability of seeds within the sediment mix
   d. What is the final height increase after the consolidation and drying of each different initial sediment layer thickness? And in how much time is this final height increase achieved?
   e. Does the application of sediment mixed with fresh, and saltwater affect the chemical parameters in the soil of the dike?
4. **Governance and financial**
   a. What are the relevant regulations and procedures, what are the possible obstacles?
   b. What is the financial advantage over business-as-usual and longer-term financing?
   c. How can stakeholders be included in the process?

3 Overview of the project from Noorderzijlvest at Lauwersoog

This chapter gives and overview about the different parts of the Growing Dike project from Noorderzijlvest at Lauwersoog. This encompasses four primary phases (2 - 5), detailed as follows:

1. Concept and Business Case development (phase prior to the TKI project)
2. Small-scale Experiment (this phase is explained in detail in Chapter 4)
3. Application Experiment (this phase is explained in detail in Chapter 5)
4. Pilot at Lauwersoog (this phase is explained in detail in Chapter 6)
5. Modelling approach (this phase is explained in detail in Chapter 7)

Each phase involved distinct consortium partners. The initial stages, including the development of the GDC, business case, and the first Plan of Actions, were undertaken by a larger consortium with EcoShape's support in 2021 (as outlined in Chapter 1). In contrast, the small-scale experiment was led and conducted by HAN University of Applied Sciences with the support of Deltares and Wageningen Marine research. This was done in parallel with the application experiment, which was led by Deltares together with Klaei bv during May 2023. Figure 3.1 shows the entire timeline of the entire Growing Dike project, from the small-scale experiment to the conclusion of the pilot.

The whole consortium performed the pilot at the Westpolderdijk near Lauwersoog. The application of the sediment started on 30th of May 2023, and extended over 2 days. The entire consortium, along with external parties and stakeholders, was invited to participate and witness the initial application of the material on the slope.

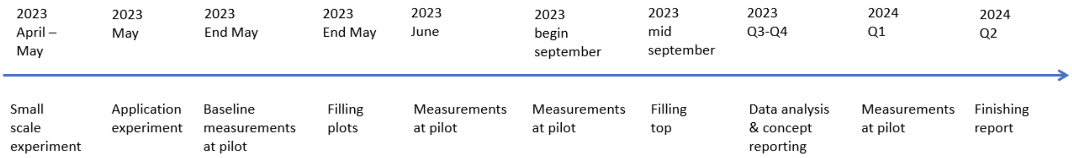


Figure 3.1: Growing Dike project timeline.

3.1 The consortium

As introduced in section 1.3, the consortium partners involved in the Phase 2 of the Growing Dike project (i.e., TKI) include: Deltares, WMR, HAN, Klaei bv, Waterschap Noorderzijlvest, and Haven Lauwersoog.

Deltares coordinates the project and is involved in all the phases outlined above: concept development, small-scale experiment, application experiment, and the pilot, in addition to subsequent analysis and monitoring.

WMR focuses primarily on investigating the impact of sediment application on the vegetation.

Consequently, WMR is directly involved in the small-scale experiment, application experiment, and the pilot, along with subsequent analysis and monitoring.

HAN (University of Applied Research) takes the principal role in executing the small-scale experiment, with support from Deltares and WMR.

Klaei bv is mainly involved in practical aspects throughout the entire Growing Dike project. This includes connect with the harbour authority in Lauwersoog, overseeing the application of material on the slope using a tractor and operator, and monitoring the pilot post kick-off.

Waterschap Noorderzijlvest is interested in the "learning by doing" concept for achieving a broad application. In the case of the Waddenzeedijk Lauwersmeer-Vierhuizergat of Noorderzijlvest, it has been observed Category I undergoes more structure formation with aging compared to Cat. II and III clay. It has now become evident that this leads to a higher susceptibility to erosion than originally thought. This may result in rejection during assessment, even though, on paper, it involves a coating based on Category 1 clay. The implementation of the GDC has the potential to delay or even prevent structure formation and mitigate the risk of rejection.

Havenbedrijf Lauwersoog is interested in the research because it can contribute to the sustainable utilization and deliverance of dredged material. The material can be employed as a building material rather than being dredged and disposed of in the Wadden Sea.

3.2 The locations

The small-scale experiment took place at the Deltares campus in Delft. The conditions were similar to those found in the field. Figure 3.2 shows the location of the small-scale experiment.

Figure 3.2: Location of the small-scale experiment within the Deltares campus in Delft.

The application experiment and the pilot were carried out in the field, specifically on the Westpolderdijk near Lauwersoog. Figure 3.3 shows the locations of the application experiment and the pilot for the Growing Dike. The red dots pinpoint the Lauwersoog's harbour, the application experiment site, and the pilot site, respectively. The yellow line illustrates the transportation route for the sediment from the dredging and mixing location (the harbour) to the application sites.

Figure 3.3: Location of Lauwersoog harbour, application experiment, and pilot. The yellow line delineates the transportation route for the material to the dike.

The application experiment took place on the same dike as the pilot but on different locations to assess similar conditions and gather insights for the pilot. The location of the application experiment is approximately two kilometres east of the pilot's site. Figure 3.4 provides an image of the dike in the proximity of the application experiment site.


Figure 3.4: Picture of the dike in the proximity of the application experiment site.

3.3 The small-scale experiment

The ripening of dredged sediment from Lauwersoog harbour for different layer thicknesses on a dike at Deltares, Delft, was investigated by HAN University of Applied Sciences. The focus of the small-scale experiment was on the effect of thickness of the sediment layer and the initial vegetation length. Two scenarios were tested: 1) 2 cm layer sediment on 4 cm long vegetation and 2) 6 cm layer sediment on 20 cm long vegetation. The freshly dredged sediment from the harbour was diluted with fresh water to a workable density before it was applied to the dike test sections. The sediment was placed on the dike test sections to the required initial sediment layer thickness on top of the initial vegetation length. The evolution of the sediment layer thickness, shear stress, water content, and organic content was measured. Table 3.1 shows the timeline of the small-scale experiment which took place in May 2023 in parallel with the field experiment introduced below.

Table 3.1: Small-scale experiment timeline.

	April				May					June			
Activity/ Time line	3/4/2023	10/4/2023	17/4/2023	24/4/2023	1/5/2023	8/5/2023	15/5/2023	22/5/2023	29/5/2023	5/6/2023	12/6/2023	19/6/2023	26/6/2023
Plan of action defined													
Sediment collection													
Materials & equipment sourced													
Sludge properties evaluated													
Pre-experimental application method tests													
Experimental setup and preparation													
Experiments running & data collection							1	2	3	4			
Post-proceesing results													

3.4 The application experiment

The application experiment was jointly conducted by Deltares and Klaei bv, with the primary objective of developing a ‘Spraying protocol’. This document comprises specific instructions aimed at achieving a homogeneous layer thickness on the dike slope.

The protocol’s development followed the “learning-by-doing” concept. By experimenting with various spraying methods, the setup that yielded the most homogeneous layer thickness on the slope was adopted for the pilot.

Chapter 5 provides a comprehensive introduction and description of the application experiment.

3.5 The pilot

The Growing Dike pilot officially kicked off on the 31st of May 2023, with the completion of application of sediment on the Westpolderdijk. Several stakeholders and the entire consortium attended the kick-off looking at the spraying of the material on the dike, while Deltares and Klaei bv were directly involved in the practical aspects of the process.

The principal outcome of the previous application experiment, the ‘Spraying Protocol’, was applied to cover the slope with the required sediment layer thickness and investigate different treatments. Several measurements and analyses were conducted before the pilot’s kick-off to set a baseline to which evaluate the development of the pilot through the monitoring performed throughout the entire duration of the pilot.

Chapter 6 provides a comprehensive overview of the main phases characterizing the starting of the Growing Dike pilot including all the measurements and analyses conducted during its duration. The results are also reported and discussed in Chapter 6, with the conclusions in Chapter 8. A discussion and synthesis of the main criteria addressed at the pilot of Noorderzijlvest, along with the principal follow-ups, is reported in Chapter 9.

3.6 Modelling the behaviour of sediment when applied on a dike slope

As part of this project the behaviour of sediment on a slope is also studied with a modelling approach. Due to the time window of applying the material on the slope in spring 2023 the modelling approach was executed parallel with the application experiments and the pilot. The results, reported in Chapter 7 and obtained during the pilot phase, allowed us to get insight in the value of the models for these types of applications.

4 Small-scale experiment

4.1 Introduction

The focus of the small-scale field experiment was on the effect of thickness of the sediment layer and the initial vegetation length. Two scenarios were tested: 1) 3 cm layer sediment on 4 cm long vegetation and 2) 6 cm layer sediment on 20 cm long vegetation. The freshly dredged cohesive sediment from Lauwersoog harbour was diluted with fresh water to a workable density before it was applied to the dike test sections (Figure 4.1). The diluted sediment was placed on the test sections to the required initial sediment layer thickness on top of the initial vegetation length. It was measured ´if ´and ´how well´ the vegetation grew through the sediment layer and the evolution of the water content, organic content, and sediment layer thickness.

Figure 4.1: Sediment placed on dike in tests sections with vegetation control plots.

Sediment was dredged from the Lauwersoog harbour in the beginning of May 2023 and transported to Deltares, Delft. The initial properties of the dredged sediment were measured (including the particle size distribution, clay, silt, and sand percentage). Figure 4.2 illustrates the particle size distribution and percentage index of clay (< 4 µm), silt (2 – 63 µm) and sand (> 63 µm) of the dredged sediment. The average particle size (d50) of the dredged sediment is 17 µm.

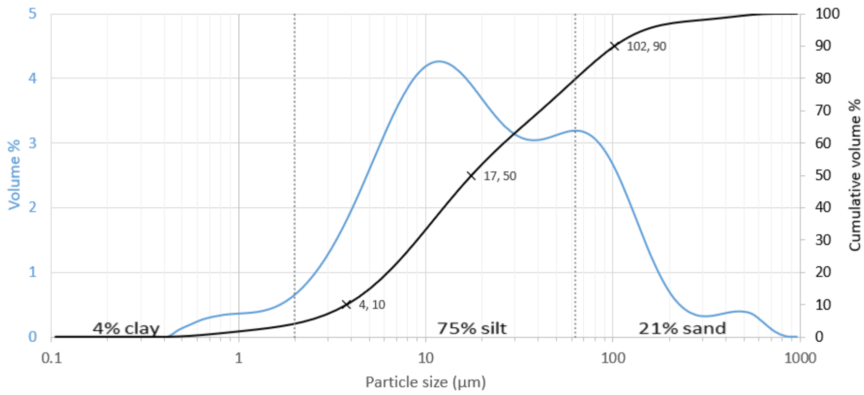


Figure 4.2: Particle size distribution and composition of sediment.

The properties of the dredged sediment dilutions with fresh water (i.e., water content and ions) were also investigated and compared. Figure 4.3 shows the bulk density of the original dredged sediment, the dilutions of dredged sediment with fresh water and the dilution of dredged sediment placed on the dike test sections. The dilution of dredged sediment used for the dike test sections consisted of 4 parts original dredged sediment and 1-part fresh water. From the graph it is evident that the bulk density and salinity of the dilutions decreased as the sediment were mixed with water. On the contrary, the pH of the mixtures increased compared to the original dredged sediment.

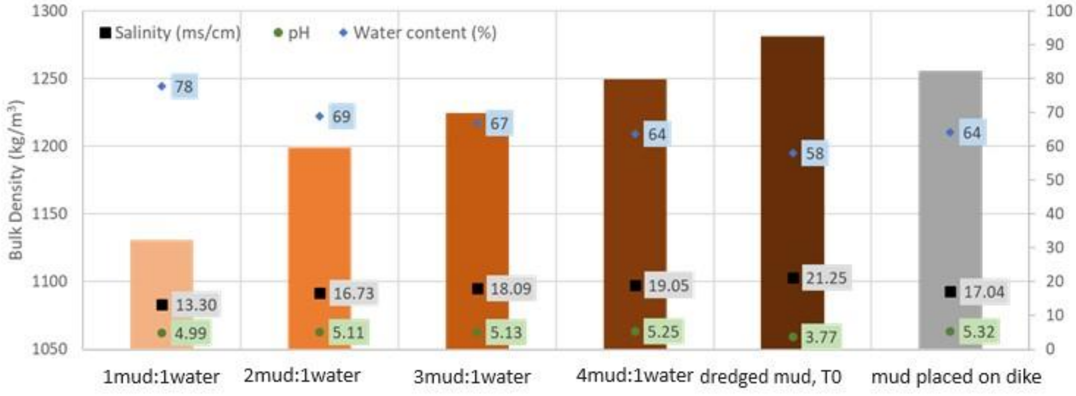


Figure 4.3: Bulk density, salinity, pH and water content of the dredged sediment and the dilutions.

Figure 4.4 shows the elements measured within the original dredged sediment, dilutions with water and the sediment dilution used on the dike test sections. The elements (Bromide, Sulfate, Ammonium, Potassium, Magnesium, Calcium, Chloride and Sodium) decrease with the dilution of water, whereas the other element (Phosphate) increases with the dilution with water. The amount of Chloride and Sodium within the dredged sediment and dilutions are significantly higher than the other elements (see y-axis of the graphs).

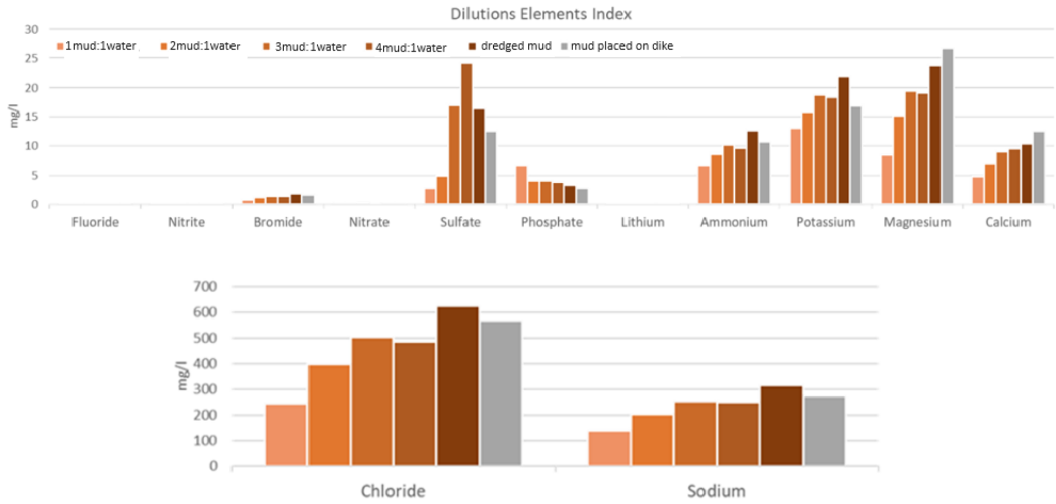


Figure 4.4: Element index of the original dredged sediment and the dilutions with freshwater.

4.2 Techniques and methods

The dredged material was diluted and mixed in proportions in a turning cement mixer and coupled with a motor. The dilutions were made based on wet weight of dredged sediment to water liquid. Mixing took place within the mixer until the diluted sediment mixture was homogenous, whereafter it was placed in a large container which was again mixed by a shovel.

The vegetation on the dike was mowed to the required length and measured with a device shown below in Figure 4.5. The sediment was poured onto the dike test sections from the top downward to the required thickness. A grid was placed on top of each test section and the sediment layer thickness was measured by placing poles at each gridline intersection as shown in Figure 4.6. Throughout the experimental testing period, sediment was sampled from left to right at each X (top), Y (middle) and Z (bottom) grid line (throughout the depth of the sediment layer) and the sediment layer thickness measured at the intersections of the grid lines. A shear vane was used to determine the shear stress of the surface of the sediment layer. Table 4.1 reports the sediment sampling timeline.

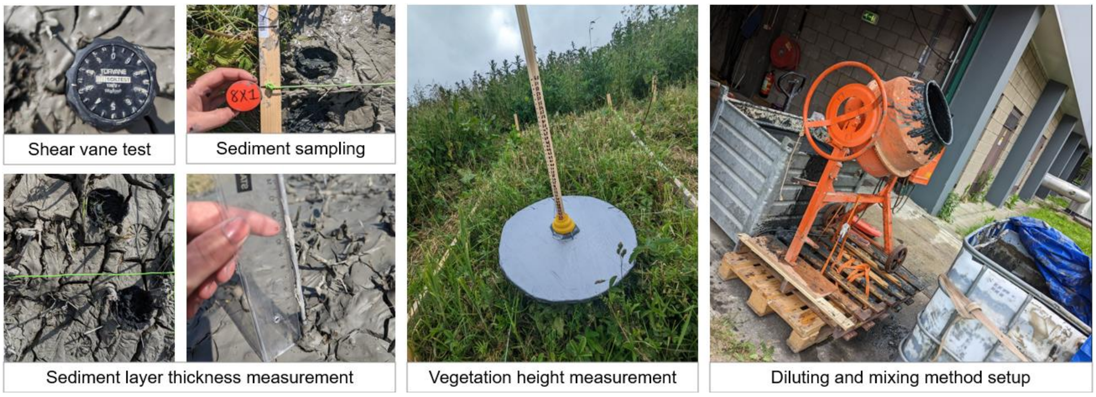


Figure 4.5: Sediment mixing and measurement techniques.

Measurements were taken on various days during the four-week testing period and the growth of vegetation and its length measured. The last shear vane test took place on day 6, whereafter the measurement equipment has reached its maximum value of 10 kg/cm2. The last sediment sampling took place on day 14 since the sediment layers of all plots were completely dry and there was no significant change in water content.

Table 4.1: Sediment sampling days.

Week 1							Week 2						
Mo	Tu	We	Th	Fr	Sa	So	Mo	Tu	We	Th	Fr	Sa	So
Day 0	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11	Day 12
veg	**slib**	**1X1**	**1X2**	**1X3**			**X4**		**X5**		**X6**		
		1Y1	**1Y2**	**1Y3**			**Y4**		**Y5**		**Y6**		
		1Z1	**1Z2**	**1Z3**			**Z4**		**Z5**		**Y6**		
Week 3							**Week 4**						
Mo	Tu	We	Th	Fr	Sa	So	Mo	Tu	We	Th	Fr	Sa	So
Day 13	Day 14	Day 15	Day 16	Day 17	Day 18	Day 19	Day 20	Day 21	Day 22	Day 23	Day 24	Day 25	Day 26
	X7			**X8**				.			.		
	Y7			**Y8**				.			.		
	Z7			**Z8**				.			.		

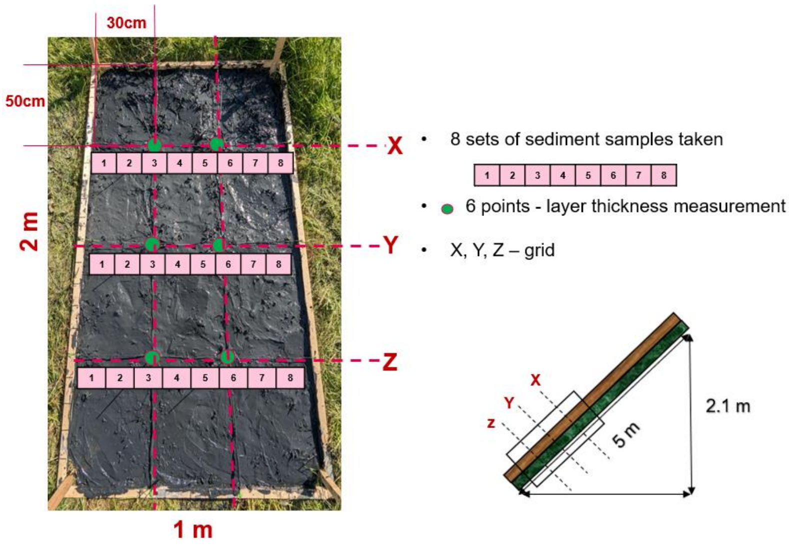


Figure 4.6: Sediment measurement grid.

4.3 Experimental execution and results

Two scenarios of sediment thickness on mowed vegetation were tested:

1) 3 cm layer sediment on 4 cm long vegetation (plot 1, 2 and 3)
2) 6 cm layer sediment on 20 cm long vegetation (plot 6, 7 and 8)

Furthermore, four sections of control of mowed vegetation of 4 cm height (plot 4 and 5) and 20 cm height (plot 9 and 10) and one section of control where the dike's vegetation was left unhindered were tested. For these sections only the vegetation height was monitored. Figure 4.7 below shows the test plots and its corresponding initial sediment layer thickness and mowed vegetation heights.

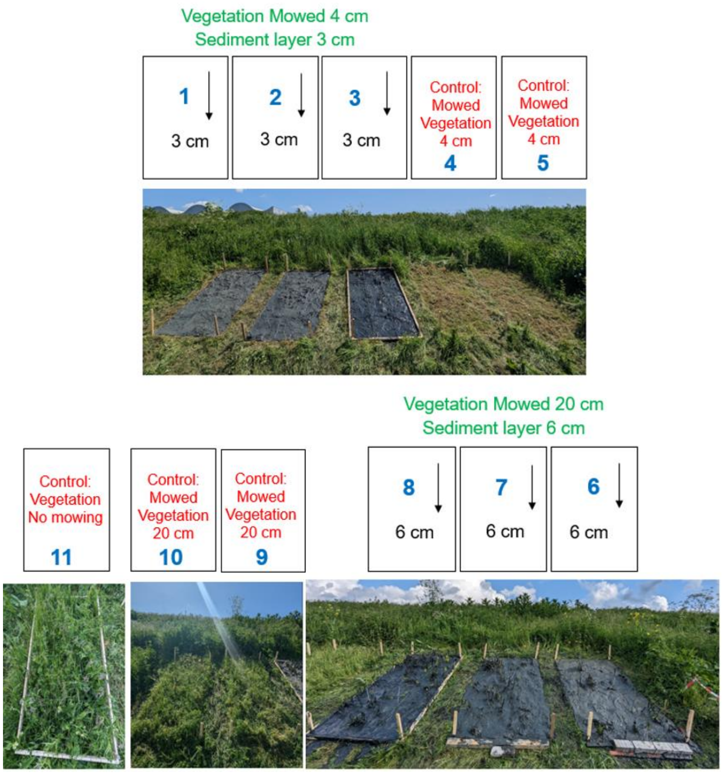


Figure 4.7: Experimental test sections with sediment layer thickness and vegetation height.

4.3.1 Sediment layer thickness and shear stress

The sediment layer thickness and the top layer shear strength was measured at multiple points on the dike test sections. Figure 4.8 shows the evolution of the average sediment layer thickness from the application of the diluted dredged sediment (day 0) to day 21 for the two test scenarios.

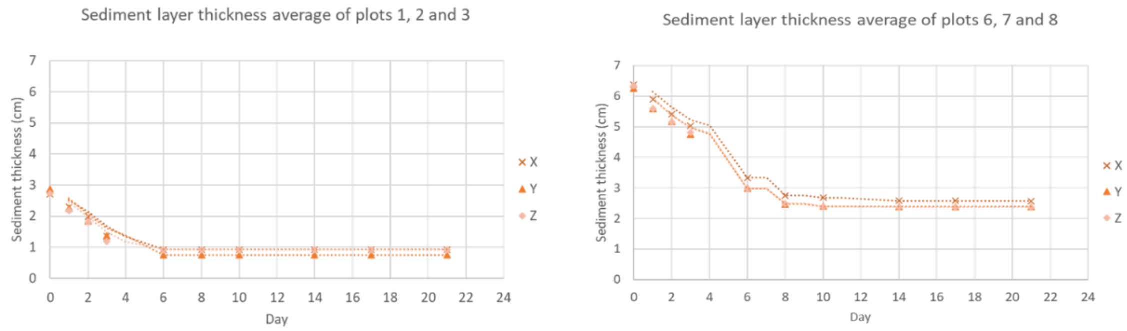


Figure 4.8: Average sediment layer thickness measured on the test plots.

The results show a decrease in sediment layer thickness taking place within the first 6 days of the test period for plots 1, 2 and 3, whereafter the layer thickness reached a constant thickness of 0.9 cm, reducing the total layer thickness by approximately 70%.

The results also show a decrease in layer thickness taking place within the first 6 days of the test period for plots 6, 7 and 8, whereafter the thickness decreases at a slower rate until day 14 before reaching a constant thickness of 2.4 cm, reducing the total layer thickness by approximately 60%.

The shear stress on top of the sediment layer was measured with a pocket shear vane (see Figure 4.5) ranging from 0 – 10 kg/cm2. The evolution of the average top layer shear stress for the corresponding test scenarios are shown in Figure 4.9 below.

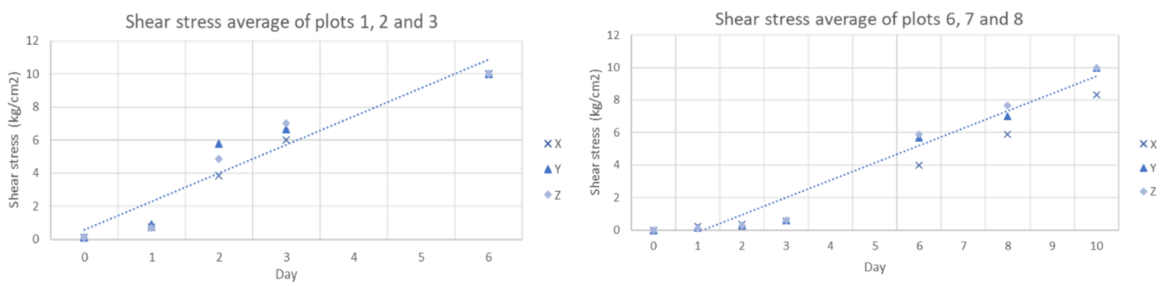


Figure 4.9: Average shear stress measured on the sediment layer surface.

The results show a rapid increase of the average shear stress on top of the sediment layer of plots 1, 2 and 3 where the maximum measured shear stress was reached after day 6. In addition, the results also show a slower increase of average shear stress for the plots with a thicker sediment layer (plots 6, 7 and 8) for the first 3 days and a gradual increase from day 3 to day 10 whereafter the maximum shear was reached. During the experiments it was noted that the top of the sediment layer of the plots with a thicker sediment layer was completely dry by day 10, forming a crust, but the sediment underneath the crust still contained moisture. This can be seen from the results of the evolution of water content within the depth of the sediment layer.

No significant changes were observed on the grid lines of X (top), Y (middle) and Z (bottom), resulting in a uniform drying, decrease of layer thickness and increase in shear stress in the plots. For plots 6, 7 and 8 a small difference was observed between the measurements from gridline X compared to Y and Z, where the X undrained shear strength measurements were slightly higher. These measurements were influenced by vegetation outside the plot area casting a shadow over the top part of these plots.

4.3.2 Sediment sampling

The evolution of water content in the water-sediment mixture applied on the dike test sections was measured. Sediment samples were taken for laboratory analysis to determine the evolution of the water content (via 'Loss on Ignition' tests), organic carbon and calcium carbonate content (via thermogravimetric analysis (TGA) tests) and throughout the four-week monitoring time.

The results of the evolution of the water content (determined via Loss on Ignition tests) within the sediment layers for the two test scenarios as well as the average high and low temperatures are reported in Figure 4.10 below.

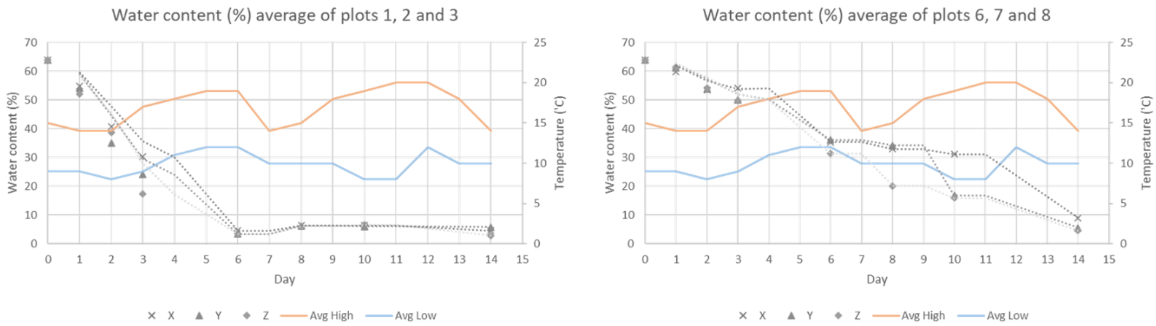


Figure 4.10: Evolution of the water content within the sediment layers.

The results show a rapid decrease of water content in the plots with the thinner sediment layer thickness (Plot 1, 2 and 3) within the first 6 days, reaching a value of 3%. A slight increase in water content is seen after day 6 as a result of an event of precipitation of 0.1 mm. The water content reached the lowest value of approximately 4% on day 14. For the plots with a thicker sediment layer, the water content decreased gradually until day 14, reaching a value of 5%.

The results of the evolution of the organic carbon and calcium carbonate content are shown in Figure 4.11 below. From the results it is shown that the organic carbon content it is almost constant. A slightly increase with time is observed. This is presumably caused by larger vegetation biomass and/or experimental error. Given the short timescale of the experiment, the effect of oxidation of organic matter can be neglected. The calcium carbonate content decreases in time. This phenomenon may be explained by a potential alteration in pH levels within the sediment environment.

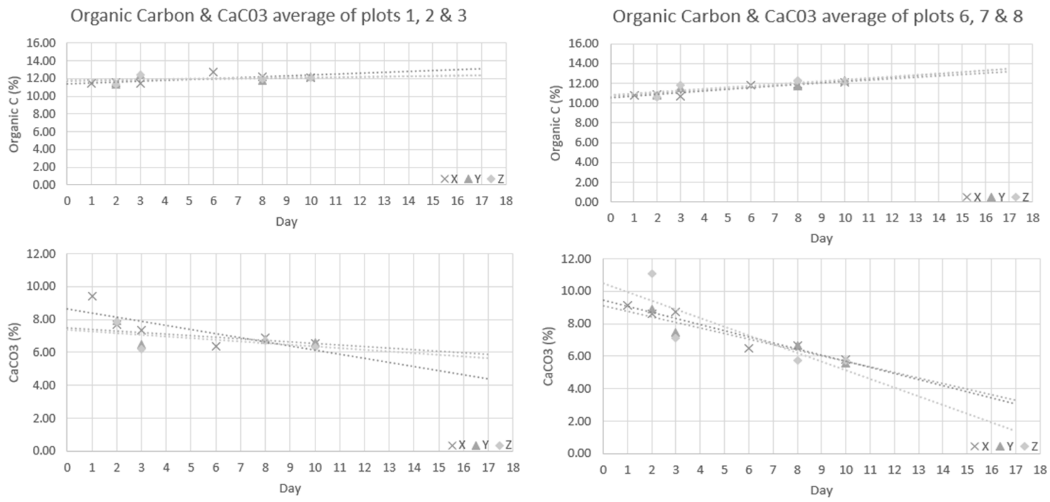


Figure 4.11: Organic carbon and calcium carbonate content evolution in the sediment layers.

4.3.3 Vegetation species and growth

The vegetation species on each test plot section was identified before and after the experimental test period and application of the dredged sediment to the plot sections. Table 4.2 shows the total amount of vegetation species per plot section and the vegetation height before and after mowing.

The dike has a lot of different vegetation types including herbaceous and grass species. The average vegetation height was measured at the top and bottom part of each plot. Four months after the experiments, the dike plot sections were surveyed once more, and a few new vegetation species were discovered were other have died. The reason behind the presence of new and dead vegetation species could be coupled to seasonal growth and phases.

Table 4.2: Amount of vegetation species and height of vegetation.

Plot	Number of vegetation species before sediment application	Vegetation height before mowing (cm)	Vegetation height after mowing (cm)	Number of vegetation species after experiment	Vegetation height after experiment (cm)
1	10	50	4.5	5 + 4(new)	30
2	14	51	4.5	10 + 2(new)	29.5
3	14	57	4.5	9 + 0(new)	43.5
4 (control)	16	55	4.5	9 + 2(new)	35
5 (control)	14	46	4.5	9 + 1(new)	38
6	12	54	21	7 + 5(new)	37
7	12	60	20	8 + 3(new)	41.5
8	18	62	20	12 + 2(new)	44
9 (control)	17	47	20.5	10 + 2(new)	33.5
10 (control)	22	57	21.5	10 + 3(new)	38
11 (control)	17	40	-	10 + 2(new)	48.5

Overall, the vegetation was able to grow through the crack formation of the dried sediment and it was visible after day 6 and day 14 of the experimental time for both test scenarios 1 and 2, respectively. After 36 days of the initial sediment placed on the dike plot sections, the vegetation growth was more prominent (Figure 4.12) and after four months, the vegetation covered 100% of the test section plots (Figure 4.13).

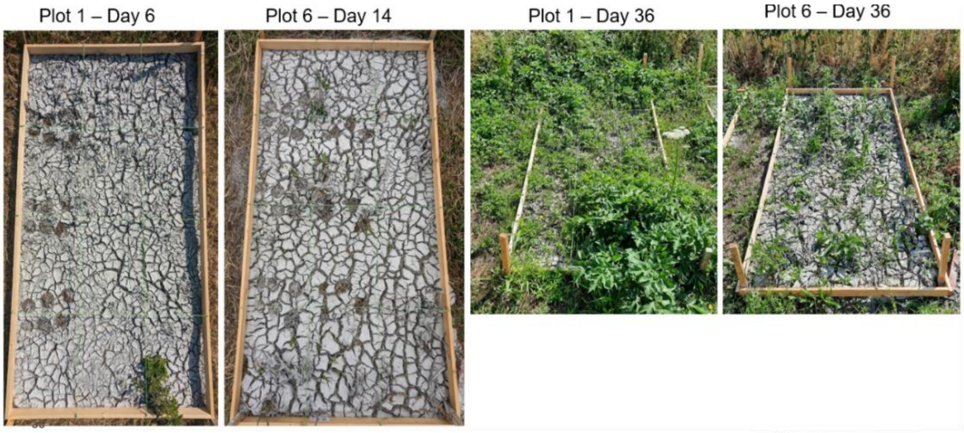


Figure 4.12: Crack formation and vegetation growth on the test plot sections.

Figure 4.13: Full recovery of vegetation on dike after 4 months.

4.3.4 Temperature and rainfall during the testing period

During the experimental test period the temperatures were ranging from an average low of 9°C and average high of 20°C. The weather conditions were overall dry with minimal precipitation during the four-week testing period, with only a few days (day 2 and 7) of 0.1 mm precipitation. The cloud coverage was also low during the test period. Figure 4.14 shows the principal weather variables considered: min/max temperature, precipitation, and wind speed.

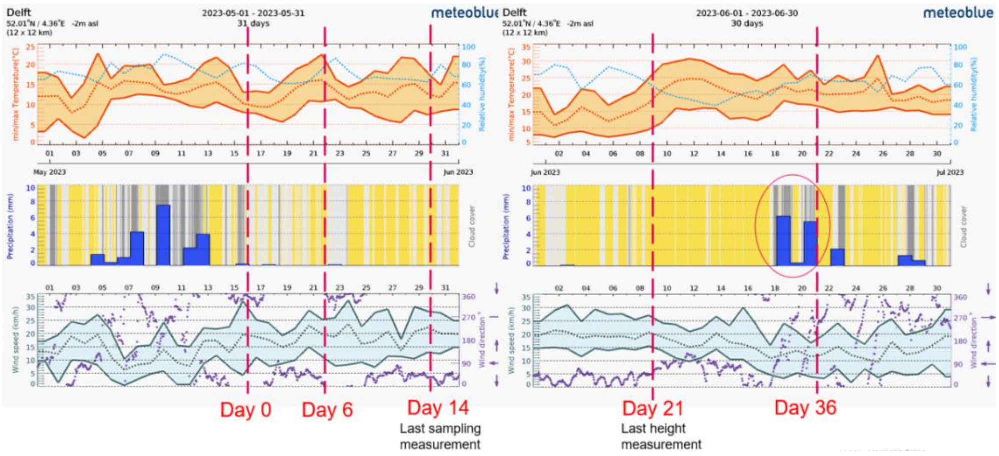


Figure 4.14: Weather conditions during the experimental test period.

5 Application Experiment

5.1 Introduction

The application experiment was a qualitative experiment conducted collaboratively by Deltares and Klaei bv, in parallel with the small-scale experiment executed by HAN in May 2023. To directly use the dredged material without allowing it to ripen in a depot had the consequence that the method with the crane was not further explored during this experiment.

The primary objective of the application experiment was to explore the most efficient way to implement the GDC in practical scenarios. This encompassed various stages, including the collection, mixing, and transportation of dredged material, concluding with its application to the dike. The principal outcome of this experiment is the development of a 'Spraying protocol', which delineates a set of instructions aimed at achieving homogeneous layer thickness across the dike slope.

Beyond the aspect of applying material to the dike, during the application experiment we investigated additional considerations. Particularly, we explored the optimal methods for executing the pilot, including sediment management, the setup of the dike with the deployment of measurement devices and the systematic collection of samples for subsequent laboratory analysis.

The principal questions that guided the application experiment are:

- **Sediment management**: How can the entire chain from dredging to application on the dike be effectively managed?
    - What is the most efficient way to collect, mix, and transport the dredged material to the application site?
    - Which viscosity of the material can be achieved by mixing the freshly dredged sediment with water?
- **Spraying method**: Which spraying technique is the most effective?
    - From the bottom or the top of the dike?
    - Which combination of tractor speed and nozzle inclination gives the most homogeneous layer thickness on the slope?
    - What is the achievable layer thickness given a certain viscosity of the material? Is it feasible to cover the entire slope?
    - How many spraying rounds are required to achieve a homogeneous layer thickness?
- **Setup of the pilot and measurements plan**: How can we prepare the slope for the application of the material and the subsequent monitoring and analyses?
    - How many different testing plots and which measurement devices are required to answer the research questions introduced in Paragraph 0?
    - How many sediment samples do we need to acquire a comprehensive overview of the biogeochemical processes?
    - How can we operate safely, without damaging or contaminating the site?
    - How can all actions and the different actors (truck operator, researchers, etc.) involved in the works be coordinated?

Location
The exact location of the application experiment is depicted in Figure 3.3. We conducted the application experiment on the same dike where we performed the Pilot, aiming to test similar conditions. Below, Figure 5.1 illustrates the specific location on the dike where the application experiment was conducted.

Figure 5.1: Location of the application experiment on the dike which is situated two kilometres to the East compared to the pilot's location.

5.2 Techniques and methods

5.2.1 Sediment Management

To prepare the material for application on the dike, it is necessary to initially dredge it and then mix it with water to achieve a viscosity suitable for the dike’s characteristics (i.e., slope angle, slope length, roughness). Following the processing of the dredged material, it must be transported to the experiment’s location for application on the dike. Combining these activities and gain experience is crucial for maximizing effectiveness during the Growing Dike chain and pilot because any issues in these processes would impact and slow down the entire project.

During the application experiment, we evaluated the most efficient way to integrate the following activities into a seamless workflow:

- Sediment collection through dredging at the harbour of Lauwersoog
- Mixing of the sediment
- Transportation of the mixed sediment to the application site

These activities were conducted at the harbour of Lauwersoog (Figure 3.3) and were primarily carried out by Klaei bv and their subcontractor.

5.2.2 Spraying method

The primary challenge in translating the GDC into reality revolved around the spraying method. Thus, the application experiment prioritized the investigation of the most effective and suitable approach to apply the material over the slope, aiming at developing a comprehensive protocol. This protocol would serve as a set of instructions to follow to get a homogeneous layer thickness on the slope.

The spraying method involve the utilization of a tractor with a slurry tank, employing a nozzle to spray the material onto the dike while the tractor moved along the dike. Our goal was to determine the optimal combination(s) of tractor speed and nozzle inclination to achieve a uniform layer thickness on the slope. It's important to note that the tractor speed directly influences the pressure in the slurry tank, affecting the velocity of the material sprayed from the nozzle.

Firstly, we started by testing the tractor's position relative to the slope. After several attempts, we opted to spray the sediment from the top of the dike, allowing us to cover the entire slope by adjusting the nozzle's inclination (Figure 5.2). Secondly, our focus shifted to finding the combination(s) of tractor speed and nozzle inclination through numerous tests, aiming for a homogeneous layer thickness over the entire slope.

These tests were conducted by Deltares together with Klaei bv at the location of the Application experiment (Figure 3.3).

Figure 5.2: Picture from the location of the application experiment during the investigation of the combination(s) between tractor speed and nozzle inclination.

5.2.3 Setup of the slope and measurements plan

The third primary focus of the application experiment focuses on two key aspects: the setup of the slope for the pilot and the development of a comprehensive measurements plan.

Regarding the setup of the slope, our objective was to explore how to measure the layer thickness and collect sediment samples in an efficient way without affecting the pilot's development and, therefore, the material placed on the slope. This point is important due to the necessity of investigating the natural maturation of sediment on a slope and the intrinsic difficulty of working on a dike slope instead of in a sediment depot.

Additionally, we focused on establishing which measurements were needed to comprehend the maturation of sediment on the slope and its impact on the vegetation underneath.

Finally, we also considered the necessity to have multiple testing plots on the dike to explore different sediment's treatments. This decision aligns with the research question inquiring the most suitable material and the most effective method to apply it on the dike.

5.3 Results

5.3.1 Sediment management

Based on the insights gained from the application experiment, we decided to streamline the process by mixing the dredged material directly at the harbour before transporting it to the dike.

Specifically, the mixing operation takes place in a container using a construction tractor equipped with a loader bucket (Figure 5.3). Water is added until the material reaches the desired viscosity, a parameter assessed through expert judgement.

Following the mixing phase, the material is pumped into the slurry tank located at the back of a tractor and then transported directly to the application site, following the route outlined by the yellow line in Figure 3.3.

The entire cycle, encompassing travel from the dike to the harbour, filling the slurry tank, and returning to the dike, takes approximately an hour. Although this duration could be optimized and shortened by employing multiple tractors and slurry tanks for material transport and application, this was not possible due to the necessity of using the same tractor, slurry tank, and nozzle throughout the project.

Figure 5.3: Mixing of the dredged sediment using a loader bucket equipped on construction tractor.

5.3.2 Spraying method

From the spraying trials conducted during the application experiment, we developed a 'Spraying protocol'. This protocol provides specific instructions to achieve a homogeneous layer thickness over the entire extension of the slope. In particular, the protocol outlines combinations of tractor speed and nozzle inclination.

To ensure uniform coverage from the top to the bottom of the slope, we recognized the need for more sprayings. Consequently, we divided the slope into six strips, each numbered sequentially from to the top (1) to the bottom (6). Figure 5.4 illustrates a schematic representation of the dike divided into six strips, each appropriately numbered.

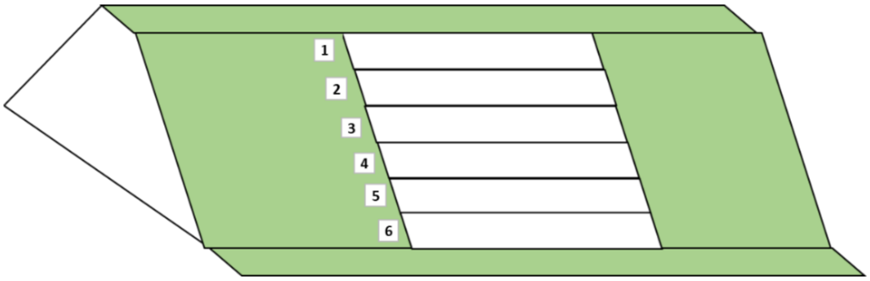


Figure 5.4: Schematic representation of the dike divided in six strips from the top (1) to the bottom (6).

To uniformly apply the sediment on each strip, we determined the most suitable combination of tractor speed and nozzle inclination. As a result, a total of six combinations were identified and are detailed in the table below.

Table 5.1: Combinations of tractor speed and nozzle inclination to apply the material on each of the six strips.

N	Gear	RPM	Nozzle angle	Tractor speed (Km/h)
1	A1	200	-15.0°	1.1
2	A1	200	-12.5°	1.1
3	A1	200	-10.0°	1.1
4	A1	200	-5.0°	1.1
5	A2	400	0.0°	2.5
6	A2	300	7.5°	2.2

Table 5.1 also includes the gear and RPM of the tractor in addition to the speed. This because these three variables are closely interconnected, and each of them influences the pressure at which the material is sprayed out from the tank.

The order in which the combinations are listed not only corresponds to the numbering of the strips on the dike, but it also enhances the time efficiency of the spraying processes. The execution of all six combinations outlined in Table 5.1 constitutes one ‘spraying round’. Additional spraying rounds are necessary when the achieved layer thickness is insufficient.

Figure 5.5 depicts the application experiment’s area on the dike following the conclusion of the tests and the implementation of the spraying protocol.

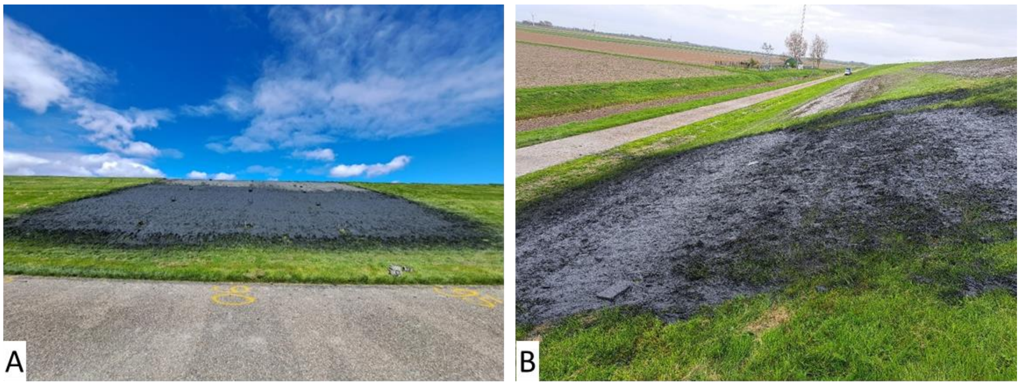


Figure 5.5: Dike slope following the conclusion of the application experiment.

It’s important to mention that the values of gear, RPM, tractor speed, and nozzle inclination, as well as their combinations presented in Table 5.1, are specific to a certain tractor, nozzle, and sediment viscosity. Consequently, if any of these tools were to change, a new spraying protocol would be necessary.

5.3.3 Setup of the slope and measurements plan

The application experiment provided insights into the most effective method for implementing the GDC in a real-world scenario. Such an innovative concept necessitates special preparation for both the persons involved and the implementation site.

To test various sediment treatments, we decided to divide the pilot’s area into several plots. A “clean” strip between each plot, along the slope, enabled us to conduct measurements and analyses without influencing the pilot’s development.

Throughout the pilot, the sediment layer thickness was measured using three main methods: rulers, Sediment Erosion Bars (SEBs), and drone analyses. Additionally, numerical modelling was employed to explore the theoretical layer thickness achievable on a slope according to fundamental mechanical equilibrium theory. The impact of sediment on the underlying vegetation were also assessed during the pilot.

Details on the different treatments explored in the Growing Dike pilot, along with the measurements and analyses, are described in section 6.2.2

6 The Pilot at Lauwersoog

6.1 Introduction

The Pilot's kick-off started on May 30, 2023, and spanned 2 days. On the first day, we applied the dredged material to the first half of the testing area on the dike. The official and representative kick-off, attended by numerous stakeholders and the entire consortium, took place on the 31st of May 2023, characterizing the completion of the spraying activities.

The results of the application experiment detailed in Chapter 5, played a crucial role in implementing the GDC and initiating the pilot. Specifically, the following aspects were defined before the pilot's kick-off based on the application experiment's results:

1. 'The Location', including the preparation of the testing area with the creation of multiple plots and the implementation of measuring instruments as well as other necessary tools.
2. 'The management and application of the dredged material', including the entire Growing Dike chain, from dredging to applying and adopting the 'Spraying Protocol' developed during the application experiment.
3. The measurements and analyses to be performed before, during, and after the pilot's kick-off.

Location
The exact location of the pilot is indicated in the aerial picture of Figure 3.3 together with the harbour of Lauwersoog and the location of the application experiment.

Figure 6.1 shows an aerial picture of the pilot area highlighted by the red lines. At the bottom of the dike, a secondary road running through the entire length of the dike has been used as the principal way to reach the pilot area.

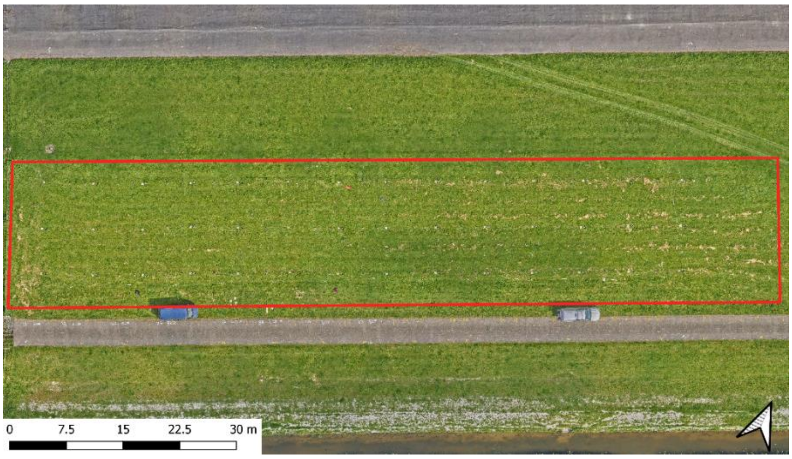


Figure 6.1: Pilot's area on the dike (Coordinate Reference System: Amersfoort / RD New, X = 217766, Y = 601761).

The pilot area is characterized by a length of approximately 102 m along the dike and a width of 19 m on the dike's slope, totalizing an area of 1938 m^2. The slope is approximately 1:3. Figure 6.2 depicts the pilot's area before the kick-off with the measurement instruments already deployed.

Figure 6.2: Pictures of the pilot's area from the day before the kick-off. The measurement instruments were already deployed.

The preparations of the pilot area were the following:

1. Plastic foil to cover the paths
2. Buckets for collecting sediment samples
3. Stone plates for measuring layer thickness
4. Sediment Erosion Bars (SEBs)
5. Temporary eviction of the sheep
6. Mowing of the grass (length ca. 13 cm)

6.2 Techniques and methods

6.2.1 Sediment management

The Growing Dike pilot consists of four 4 main phases, each revolving around a common actor: sediment. The phases are outlined and elaborated below:

1. Dredging
2. Processing
3. Transportation
4. Application

Dredging

Figure 6.3 illustrates an aerial view of the Lauwersoog harbour, with the dredging area highlighted by the yellow box and the unloading and mixing location marked by the red and red box. The sediment is dredged from the bottom of the water column using a squeeze barge and transferred to the vessel. When the ship is sufficiently loaded, it unloads the material directly in a mixing container at the location indicated by the red box in Figure 6.3.

Figure 6.3: Aerial view of Lauwersoog harbour. The yellow box denotes the dredging location, while the red box indicates the unloading and mixing area.

Processing

At the unloading site, an excavator places the dredged material directly into a mixing container (Figure 6.4). Water (both fresh and saltwater) is added to the sediment and mixed using a loader bucket equipped on a construction tractor. The desired mixture viscosity is determined through expert judgement, considering the results of the application experiment (2 dredged material on 1 water (2:1)).

Figure 6.4: Unloading dredged sediment from the vessel using an excavator at the Lauwersoog harbour.

Transportation

The mixture is subsequently pumped from the mixing container into the slurry tank of the same tractor used for spraying the sediment on the dike. From the Lauwersoog harbour, the mixture is transported to the pilot's location, following the route indicated by the yellow line in Figure 3.3.

Application

Figure 6.5 illustrates a photo taken during the pilot's kick-off. The sediment is sprayed from the top of the dike through a nozzle equipped on the back of the slurry tank. By adopting the "Spraying Protocol", it is possible to achieve a homogeneous layer thickness across the entire slope of the dike.

Figure 6.5: Application of the sediment from the top of the dike through a nozzle equipped on the slurry tank.

6.2.2 Measurements and monitoring

To address the research questions introduced in Chapter 2 and drawing from the experience gained during the application experiment, we opted to explore seven different treatments of the dredged sediment, as detailed in Table 6.1. These treatments encompassed variations in the achieved layer thickness and the mixing process of the dredged material. Each treatment was tested on two plots (duplicate), resulting in a total of 14 plots, along with the inclusion of two additional reference plots.

We investigated two treatments involving the variation of layer thickness: 2 cm or 5 cm. As described in the following paragraphs, these two thickness values were not precisely achieved during the pilot due to the challenge of applying a specific sediment thickness on a slope. One spraying round was sufficient for the first layer thickness, while two spraying rounds were required to achieve the second thickness.

In terms of mixing the dredged material, we aimed to test the effects of both fresh and saltwater. Consequently, we utilized both to create two separate mixtures with similar viscosity. Additionally, we explored the effectiveness of enhancing and boosting vegetation (re)growth by adding seeds to the mixture before its application on the dike.

Table 6.1: Overview of the treatments explored in each plot. Each plot was subjected to a different combination of layer thickness, addition of seeds, and mixing with either fresh or saltwater.

Plots	1	2	3	4	5	6	7	Ref.
Thickness (cm)	2	5	2	5	2	2	5	0
Seeds	No	No	Yes	Yes	No	Yes	Yes	No
Water	Fresh	Fresh	Fresh	Fresh	Salt	Salt	Salt	No

Figure 6.6 illustrates a schematic representation of the 14 testing plots, along with two references plots, as well as showcasing the various treatments investigated. Each plot is labelled with a number (from 1 to 7) and a letter (“a” or “b”). The number signifies the treatment being tested in that plot, while the letter indicates the duplicate. The two reference plots are labelled as C1 and C2, respectively.

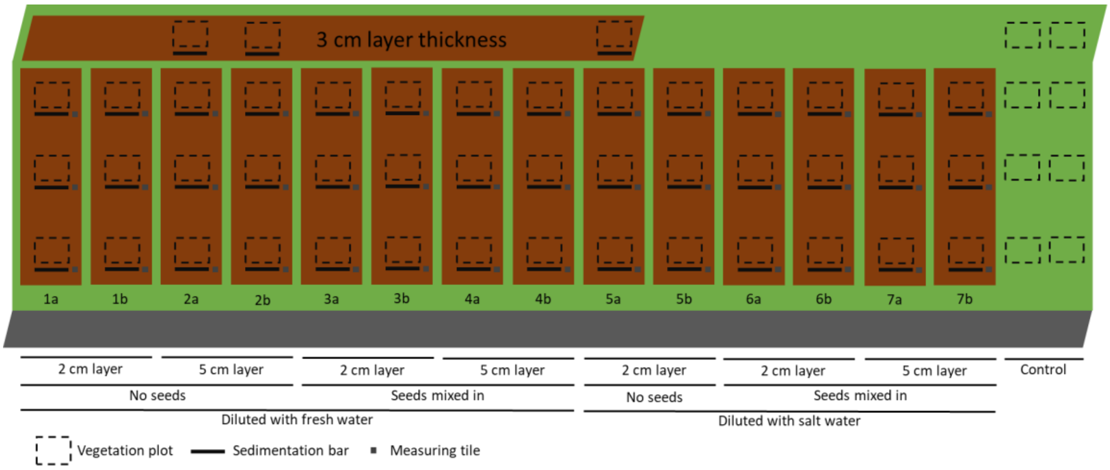


Figure 6.6: Schematic representation of the slope during the pilot, comprising 14 testing plots on the slope and one on the crest. The investigated treatments for each plot are detailed at the bottom.

Each testing plot is approximately 6x20 m and is separated from the others, allowing for analyses and measurements between plots. Within each plot, there are three distinct sub-areas (bottom, middle, and top, numbered as 1, 2, and 3, respectively), serving as “fundamental unit areas”. These sub-areas are very important because all measurements and monitoring analyses were conducted for each of them. Specifically, we assessed the development of layer thickness over time, the impact of sediment on vegetation, and greenhouse gas fluxes. The division of the slope into three areas provides a comprehensive and detailed overview of the Growing Dike implementation, capturing possible variations from the top to the bottom of the dike.

Figure 6.6 also presents the deployed measurement devices in the field during the pilot, aiming to investigate layer thickness over time and the impact of sediment application on vegetation in each sub-area. Sediment Erosion Bars (SEBs), utilized for monitoring layer thickness, are represented as horizontal lines, while the “Measuring tiles” used to calibrate the reference surface for drone analysis are depicted as small circle next to the SEBs. The “Vegetation plot”, also outlined in Figure 6.6 with dashed lines, corresponds to the areas where vegetation analyses were conducted throughout the pilot. A more detailed explanation of the functioning and analysis with these devices is provided in the following paragraphs.

Furthermore, we applied a 3 cm thick sediment layer on the crest of the dike, as illustrated in Figure 6.6, only three months after the kick-off. Our goal was to investigate the sediment layer thickness development, re-growth of the vegetation, and GHG fluxes during a later stage of the growing season.

Figure 6.7 provides an aerial view of the pilot area five days after the kick-off, with the various testing plots highlighted by red polygons. It’s important to note that the sediment layer applied on the crest of the dike is not visible in Figure 6.7, as it was applied only three months after the kick-off.

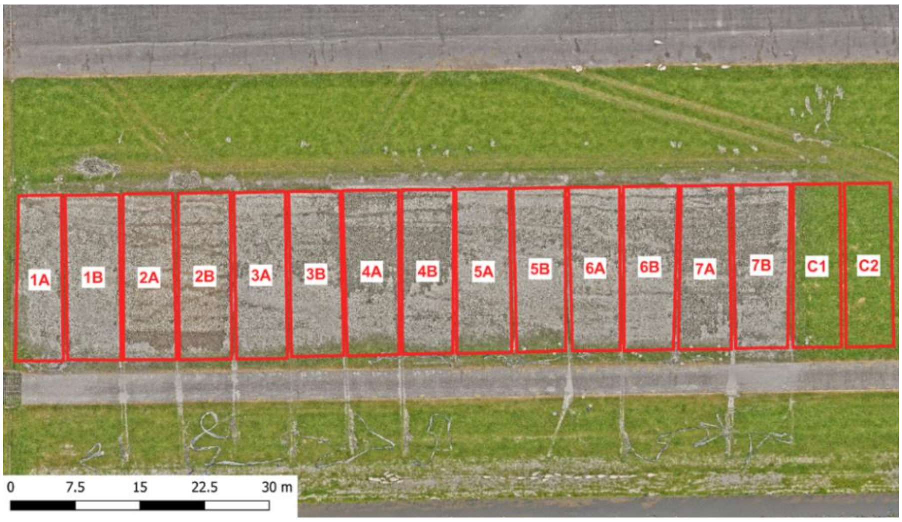


Figure 6.7: Aerial view of the slope five days after the sediment application. The testing plots are identified by their label and highlighted by the red polygons.

6.2.3 Sediment and soil composition

To gain deeper insights into the properties and composition of both the dredged and applied sediment, as well as the dike's soil, a series of laboratory analyses were conducted. The main objective of these analysis was to conduct a quantitative evaluation of the chemical compositions and determine variations in both the sediment layer and the underlying soil. This was achieved by performing Thermogravimetric Analysis (TGA) to determine water content and organic matter and Ion Chromatography (IC) to measure dissolved salts and nutrients. The study also assessed the impact of the applied sediment on the chemical parameter variations in the (dike) soil underneath. Specifically, the analyses enable us to investigate the potential desalination or salination processes occurring between the applied sediment and the underlying soil. These processes could influence dike parameters and have implications for vegetation survival and (re-)growth.

Specifically, the analysis encompassed both the physical properties, such as the rheology, and the chemical composition, including water content, organic carbon, and the most relevant ions. This was done for three distinct types of samples:

- Freshly dredged sediment (untreated)
- Sprayed sediment (treated)
- Soil from the dike (soil sample)

Samples of the freshly dredged sediment were collected in triplicate directly from the mixing container at Lauwersoog harbour. These samples were analyzed to exclusively determine their water and organic content. Particularly, these analyses were conducted at the beginning of the pilot to gain insights into the natural composition and properties of the sediment.

Additionally, during the initial week of the pilot, sediment samples from the layer covering the dike's slope were systematically collected for laboratory analysis. This initial analysis allowed us to establish a baseline for the evolution of both physical and chemical properties over time. Particularly, TGA and IC analysis were conducted to determine the content of various chemical components, including water content, salt (NaCl) content, organic matter, and other ions (bromide, chloride, sodium, ammonium, nitrate, phosphate, sulfate). Before the pilot kicked-off, soil samples were also collected directly from the dike to examine the soil's inherent chemical composition under natural conditions. The same chemical analyses (i.e., TGA and IC) were conducted on these soil samples as were performed on the applied sediment.

Three months after the beginning of the pilot, samples of the applied and matured sediment, as well as of the underlying soil were collected. This allowed us to determine the differences in chemical composition after sediment maturation and investigate the impact on the soil beneath.

To streamline and maximize the outcomes from the two sampling campaigns performed during the first three months of the pilot, a protocol was applied. Particularly, regarding the applied sediment, a single sample from each plot was collected. However, for each of three specific plots (1B, 4B, and 6A), three samples were collected, namely from the bottom, middle and top of the slope. This was done to ensure the homogeneity of the sediment within each plot and, therefore, to confirm that the collected samples were representative of the actual composition of each plot. Particularly, for plot 1B, 4B, and 6A we collected three sediment samples. The analysis results confirmed that the chemical composition of the sediment samples within a plot was homogeneous enough to justify collecting only one sample from each plot.

We adopted a similar approach for the soil sediments. One soil sample was collected from each plot, with exception of plots 1B, 4A, and 6A, from which two samples were collected. Also in this case, the analysis results confirmed that the chemical composition of the soil samples within a plot was enough homogeneous to allow collecting only one sample from each plot.

6.2.4 Layer thickness development

To evaluate physical development, such as maturation and consolidation of the material applied on the dike, we systematically monitored the layer thickness employing three distinct methods outlined and briefly explained below:

1. Ruler
2. SEB (Sediment Erosion Bar)
3. Drone

In addition to these three methods, we quantitatively assess the theoretical layer thickness achievable through spraying rounds by numerical modelling. This is presented in Chapter 7.

Measuring with rulers

For every sub-area within each plot, the layer thickness was monitored for the first week only with a ruler. The position where the layer thickness measurements were performed is situated on the side of each sub-area, near the tiles used for the drone analysis. In this way we could conduct the measurements without perturbating the material layer and its maturation on the slope. The ruler utilized exhibits a precision of 1 cm. Layer thickness measurements were conducted in triplicate for each sub-area, yielding a total of 9 measurements per plot.

The initial layer thickness values, acquired on the first day of the pilot, enabled us to establish the baseline for the sediment thickness evolution and to estimate the total volume of material applied to each testing plot and entire slope.

Measuring with SEB

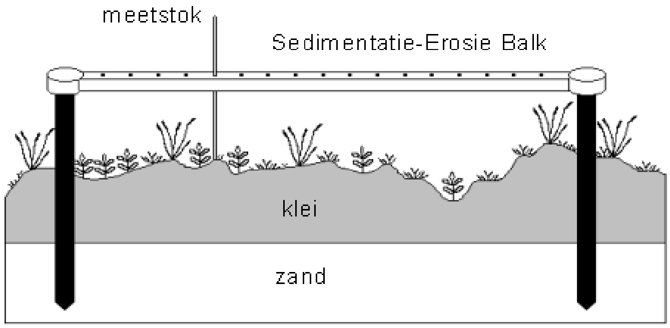


Figure 6.8: Graphical representation of the Sediment Erosion Bar (SEB), showing the poles (black) and the bar with holes on top of it. By measuring the distance through the holes from the bar to the underlying material and vegetation, the sedimentation or compaction can be measured.

With a Sedimentation Erosion Bar (SEB), visible in Figure 6.8, the applied layer thickness and the layer's compaction over time have been measured. With an accuracy of 1.5 mm, a SEB measurement is usually utilized in salt marshes to assess sedimentation and erosion (Nolte et al., 2013). Two plastic poles spaced two meters apart are positioned at the top, middle, and lower sub-area of each dike plot (Figure 6.6). There are 17 permanent spots between the two poles where the distance from an aluminium bar to the ground is measured when it is placed on top of them. Calculating sedimentation or compaction involves comparing the measurement to an earlier measurement. Measurements with the SEB bar was taken before the pilot’s kick-off, particularly on the 24th of May 2023. Following the application of the material, the SEB was measured on the 6th, 7th, 8th, 9th, 12th, 14th, and 16th of June, and on the 31st of August 2023. Before the next growing season on 21st of March 2024 the SEB height was measured for transect 2 and 5. The precision of the June 2023 measurements is poorer since the distance was rounded to the nearest centimetre.

A t-test was used to statistically compare the two different layer thickness treatments and the position on the slope (top, middle, bottom) for the analysis.

Measurements using drone

The dike vegetation was mowed prior to taking the drone photos to minimize vegetation interference. The drone took numerous overlapping photos while flying in an automatic route over the dike area. Asphalt nails were positioned at the road to generate reference points for the image. An accurate GPS (RTK-DGPS) was used to measure the surface elevation for these reference points in relation to NAP (mean sea level). Three times, before the pilot’s kick-off (24th of May 2023), following the application of the dredged material (5th of June 2023), and three months later (13th of September 2023), drone photos were taken.

These overlapping photos can be used to produce an orthophoto and a digital surface model. Because the vegetation height is included in the digital surface model, it may have significant errors. The elevation following the application of the dredged material was lower than the initial elevation including vegetation, because the vegetation was buried by the dredged silt. Additionally, the variations in height are comparable to the 2 cm vertical error.

Utilizing the orthophoto, the vegetation cover was assessed. Vegetation and bare land were categorized in the orthophoto in order to determine the overall amount of vegetation cover from the drone photos. A random forest model based on pixels was used for the classification, and it had a 1.69% error rate.

6.2.5 Vegetation

Three permanent quadrants (PQ) measuring two meters by two meters have been positioned in each sub-area forming each testing plots on the slope. The measurements of the vegetation have been evaluated in these PQs before the application of the material and after three months. Using the Londo vegetation scale (Londo, 1976), the species cover has been ascertained, and an estimate of the vegetation height has been made. Using an Anova (i.e., a statistic test), the important effects of layer thickness, the presence of seeds, and the dilution of fresh or salt water have been studied for the cover of grasses and bare soil.

Soil samples were collected at a reference plot, plots 1a, 1b, 2a, 2b, 6a, 6b, 7a, and 7b, on 7 September to determine the rooting depth. At the sub-area located in the middle of the dike slope, just one soil core per plot was collected. The soil cores were split into 2.5 cm pieces and had a depth of 20 cm. The approach from the Toetsen Veiligheid Primaire Waterkeringen protocol was used to estimate the number of roots in each section (Min V&W, 2007).

6.2.6 Greenhouse Gas fluxes

Figure 6.9 illustrates the entire dredging and construction chain characterizing the GDC, showcasing the greenhouse gas fluxes for each single phase. In normal situation (i.e., pre-dredging), the emissions remain relatively constant. However, during dredging, transportation, and material application/disposal, the emissions increase, reaching their peak for the entire chain. As the dredged material is placed and begins maturing, the organic matter oxidizes, and emissions continue until organic carbon in the sediment is depleted. Subsequently, during this phase, the emissions decrease until vegetation grows through the newly applied sediment layer or new vegetation colonizes the material. At this point, vegetation starts absorbing carbon dioxide (CO_2) from the atmosphere, reversing the emissions balance.

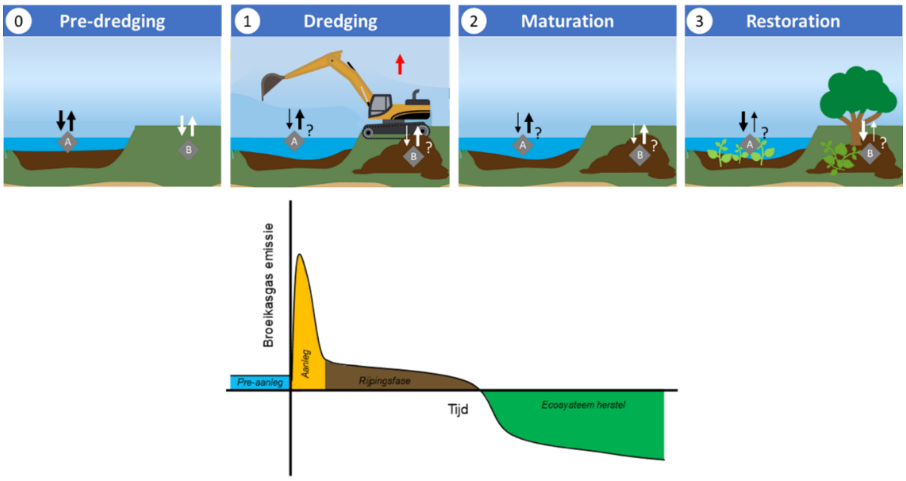


Figure 6.9: Schematization of the dredging and construction chain with the GHG fluxes highlighted and qualitatively presented for each phase (Figure: Deltares, Witteveen+Bos. Project: "Duurzaam Nat Grondverzet voor klimaat en natuur (DUNAG)", 2022).

To investigate and quantify the possible impact of the GDC on the carbon cycle, we investigated the GHG fluxes from the surface of the slope of the dike at three different times: before, just after, and after 3 months from the application of the dredged sediment. In addition, variations between the different treatments were examined to identify the scenarios with least GHG emissions.

The study employed the Microportable Greenhouse Gas Analyzer (MGGA), a portable in situ gas monitoring system that measures Carbon Dioxide (CO_2) and Methane (CH_4) concentrations within a small cylindrical greenhouse placed on the surface whose GHG fluxes need to be determined. The chamber is connected to the machine forming a closed circuit. Air is circulated through the machine, which measures the greenhouse gas concentrations by infrared detection every second. The fluxes can be positive in case the concentration is increasing, meaning emissions of GHG, or negative, meaning that the concentration is decreasing due to uptake and absorption processes. On this basis, the rate of GHG emission or uptake is determined. This device produces multiple measurements per second that can be visualized in real-time, allowing for the immediate detection of potential leakages that could affect the results. The MGGA is adaptable to various environments and weather conditions, making it suitable for deployment on different soil types and water bodies. Figure 6.10 shows a schematic representation of the MGGA with the cylindrical greenhouse placed on the surface whose GHG fluxes need to be measured.

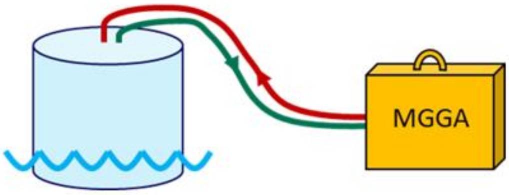


Figure 6.10: MGGA (Microportable Greenhouse Gas Analyzer)

The measurements were conducted at three specific spots within each sub-area of only one plot for each treatment (excluding the reference), totalling 7 plots with 9 measurements each. The homogeneity of the vegetational cover of the slope allowed to conduct only three measurements in the reference plot. For each measurement, the concentration of CO_2 and CH_4 were recorded over 1:30 minutes, and the resulting data were analyzed using an R script to establish the fluxes expressed in mg/m^2/day, commonly reported in scientific literature. Additionally, CH_4 fluxes were converted to CO_2 equivalents for consistent comparison between these two gasses.

It's important to specify that we conducted measurements of GHG fluxes from the slope on specific dates, providing only a snapshot of the fluxes for certain moments during the pilot. Furthermore, these measurements were taken under specific environmental and weather conditions, focusing solely on the light phase of photosynthesis, and excluding vegetation respiration. Although these measurements do not provide a comprehensive view of the impact of the Growing Dike on the carbon cycle, they offer insights into the changes in fluxes resulting from the application of dredged material and vegetation burying.

6.2.7 Weather conditions

In Lauwersoog and on site of the Growing Dike pilot, weather conditions (i.e., temperature, humidity, wind, rain) are recorded using the Vantage VUE Integrated Sensor Suit weather station (mode 6357) with Vue registration console.

The weather data were primarily used to identify weather events that could have affected the consolidation of the applied sediment.

6.3 Results

In this paragraph, we present the results of the analysis of the data collected both before the start of the pilot and during its execution. Specifically, Deltares, Klaei bv, and Wageningen University were actively involved in monitoring of the key variables outlined in the previous paragraph, crucial for this project.

6.3.1 Sediment and soil composition

Freshly dredged sediment

The water content total and organic content of the freshly dredged material were analyzed in triplicate, and the results are detailed in Table 6.2.

Table 6.2: Water content total and organic content for the freshly dredged sediment.

Sample	Water content total (%)	Organic content (%)
1	59	6.6
2	59	7.2
3	59	8.0

The water content total is determined by subtracting the dry mass of the sample (after 24 hours in the oven at 105 °C) from the total mass of the sample, divided by the total mass of the sample. For the freshly dredged sediment, this value is consistently uniform and equal to 59%. In contrast, the organic content varies more significantly, ranging between 6.6% and 8.0%. It’s important to note that the organic content pertains to the dry mass of the sample and not to the total mass, as is the case with the water content total.

Sprayed material

Concerning the sediment applied to the dike, TGA and IC analyses were conducted on one sample from each testing plot at the beginning of the pilot. The results of the TGA are detailed in Table 6.3.

Table 6.3: Water, organic, and calcium carbonate content just after the application of the sediment as determined by TGA.

Sample	Water content (%)	Organic content (%)	Calcium carbonate content (%)
1A	62	12.5	7.4
1B	62	12.4	7.5
2A	70	13.5	10.0
2B	68	12.9	8.2
3A	64	12.0	6.5
3B	61	12.0	8.8
4A	65	11.6	8.1
4B	64	11.7	8.1
5A	66	11.0	9.7
5B	68	11.0	9.8
6A	62	10.9	9.2
6B	60	10.7	9.6
7A	65	11.1	9.0
7B	62	10.7	9.4

The average water content is 64%, slightly higher than that of the freshly dredged sediment, due to the mixing with fresh or salt water. The average organic content is 11.7%, while the calcium carbonate content is 8.7%.

In addition, samples of the applied material were collected also daily throughout the first week of the pilot. These samples were analyzed to investigate the variation of water content over time, allowing us to explore the dewatering and drying processes of the sediment. Specifically, we investigated the differences between plots characterized by the 2 cm or 5 cm treatment. Figure 6.11 illustrates the variation in water content total for the two treatments during the first week of the pilot.

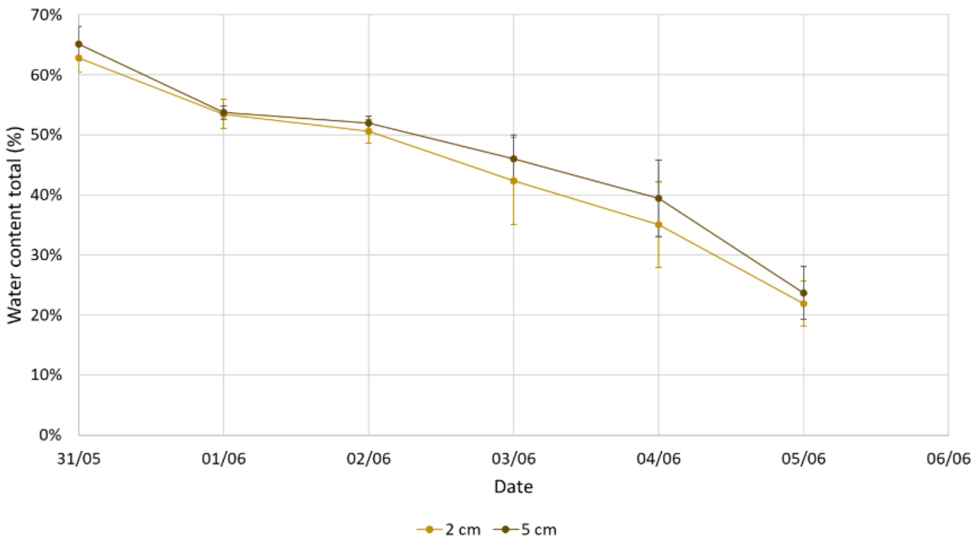


Figure 6.11: Variation of the average water content total of the applied sediment over the first week of the pilot for the plots with 2 cm (yellow line) and 5 cm (brown line) treatment.

Both treatments exhibited a continuous decrease in water content total throughout the entire first week of the pilot, with a total decrement of approximately 40%. Specifically, the 2 cm treatment reached a water content total of 22% after 5 days, while the 5 cm treatment of 24%. There was no significant difference between the two treatments. Both treatments experienced substantial dewatering and drying during the initial week of the pilot, due to the relatively sunny weather and high temperature recorded in June 2023.

Soil

We conducted TGA and IC analysis also on one sample from each testing plot for the soil before the sediment application. The TGA results are presented below in Table 6.4.

Table 6.4: Water, organic, and calcium carbonate content of the soil before the sediment application determined by TGA.

Sample	Water content (%)	Organic content (%)	Calcium carbonate content (%)
1A	22	9.0	6.3
1B	23	9.6	6.9
2A	24	8.7	7.1
2B	25	9.5	6.9
3A	24	9.0	7.0
3B	28	10.0	7.0
4A	23	9.1	7.7
4B	24	9.0	7.9
5A	25	10.1	6.7
5B	21	8.6	7.6
6A	23	9.1	7.7
6B	27	9.8	6.7
7A	26	9.6	6.3
7B	22	7.5	7.3
C1	26	9.6	6.9
C2	27	9.5	6.8

All the three analyzed variables exhibit uniform values across the testing area of the dike. The averages stand at 24%, 9.2%, and 7% for water, organic, and calcium carbonate content, respectively.

It’s important to mention that the samples of both the sediment and the soil were stored in plastic bags. Consequently, some water may have evaporated from the material, even though it remained in the bag, affecting the water content of the samples. Based on expert judgement, these results likely underestimate the water content by approximately 5%.

Comparison between sediment and soil chemical composition during the first three months

The IC analysis, conducted for the samples which were collected at the beginning of the pilot and after three months, allowed us to assess the variations in the chemical composition of both the applied sediment and the underlying soil over time and across different plots. Specifically, the potential impact of the applied material on the underlying soil was examined with particular attention to the ions that could potentially be washed away, infiltrate into the soil, and subsequently affect the survival and (re-)growth of vegetation.

It’s important to note that conducting IC analysis at only two specific time points didn’t permit the investigation of intermediate variations during the initial months. Only the composition at the start and three months after could be examined and compared. In addition, to gain insights into long-term trends and variations in both sediment and soil composition, further sampling and analysis are required over a more extended period.

Figure 6.12 illustrates the ions (i.e., bromide, chloride, sodium, ammonium, nitrate, phosphate, and sulphate) concentration, along with the organic (expressed as % of the total mass) and salt content for each plot. Particularly, it reports the results for the two distinct time points: at the beginning of the pilot and three months later. These results cover both the sediment and soil, enabling us to assess spatial (between plots) and temporal (during the initial three months) variations. The plots show data variations only after three months, with most differences between plots being minor and hidden by biological variation. Therefore, we limit our comparison to the composition of the soil and sediment for the two treatments involving different sediment layer thicknesses.

Figure 6.12: Content of bromide (Br), chloride (Cl), sodium (Na), ammonium (NH_4), nitrate (NO_3), organic carbon, phosphate (PO4), and sulphate (SO_4) in mg/L porewater for each plot, including both the sediment (mud) and underlying soil. Salt content is expressed in g/L porewater. Timepoint 1 is at the beginning of the experiment, Timepoint 2 is after 3 months.

Figure 6.13 and Figure 6.14 and present the concentration of bromide, chloride, sodium, ammonium, nitrate, organic carbon, phosphate, and sulphate in both the soil and sediment for the two time points considered: the beginning of the pilot and three months later. These concentrations, averaged over the two sediment layer thickness treatments (i.e., 2 and 5 cm), are depicted as boxplots. Specifically, Figure 6.13 displays the concentration in mg/L porewater, while Figure 6.14 reports the concentration in mg/kg of dry weight (DW). The latter format particularly enhances the visualization of sodium and sulphate concentration in this specific case.

During the initial three months, between the two sampling campaigns, the concentrations of bromide, chloride, sodium, ammonium, and nitrate in the soil increased. Conversely, these ions' concentration, with exception of nitrate, in the sediment decreased, suggesting that they infiltrated into the soil after being washed off, thereby altering its chemical composition. This pattern was observed across both sediment layer thickness treatments. Notably, the concentration of nitrate within the sediment remained relatively constant during this period.

As shown in Figure 6.13, the organic content in the soil increased while it decreased in the sediment. The decrease in the sediment could be attributed to the oxidation of organic matter, which results in the emission of greenhouse gases such as carbon dioxide and methane. Conversely, the increase in the soil's organic content could be due to the growth of new and denser roots in response to the disturbance caused by the sediment application, enabling vegetation to (re-)grow through the sediment layer. A contribution of soluble organic matter leaching from the sediment into the soil can also not be excluded.

Both phosphate and sulphate concentration increased both in the soil and sediment. This suggests that:

- The increase in phosphate and ammonium is likely due to mineralization, a process where chemical components in organic matter are decomposed or oxidized into more readily available forms. This mineralization could be triggered by changes in the chemical composition of the environment following the application of sediment.
- The increase in sulphate the soil and sediment is probably the result of drying of the marine sediment, but it requires further analyses to clarify the exchange dynamics between the two layers.

From the analyses results and comparisons reported Figure 6.13 and Figure 6.14, the sediment layer thickness treatments were shown to not have a strong effect on the chemical composition of the soil.

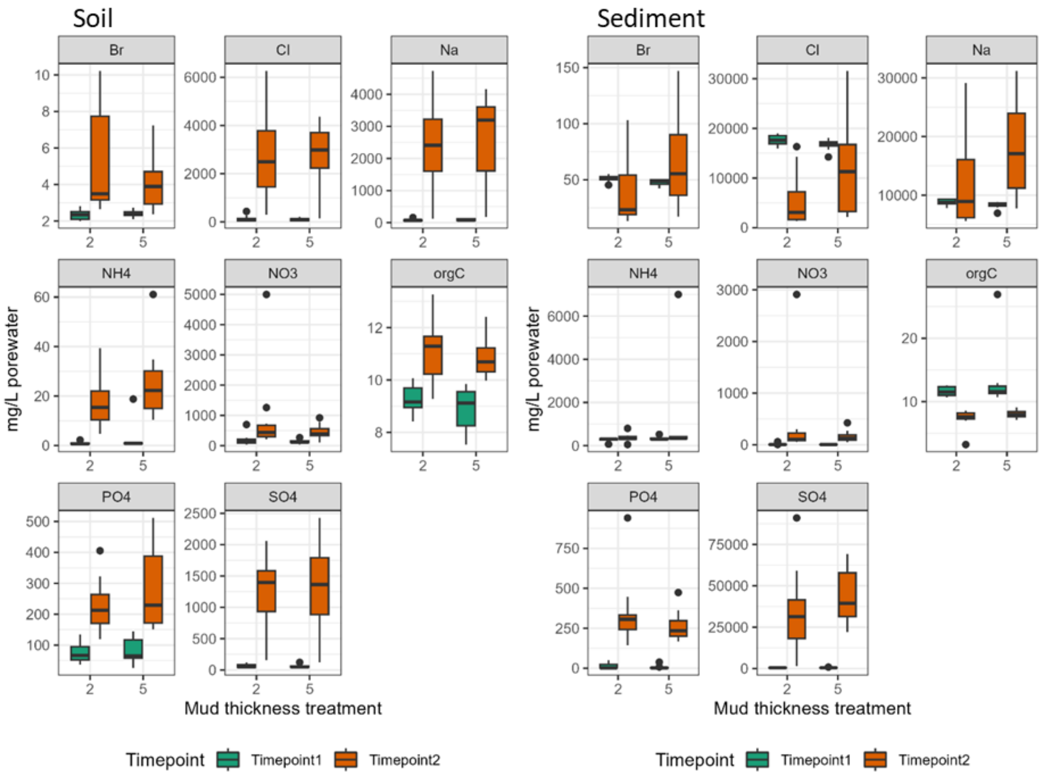


Figure 6.13: Concentration of bromide (Br), chloride (Cl), sodium (Na), ammonium (NH_4), nitrate (NO_3), organic carbon, phosphate (PO_4), and sulphate (SO_4) in mg/L porewater for each plot, including both the sediment and soil underneath. In addition, the difference between the treatments of sediment layer thicknesses is reported.

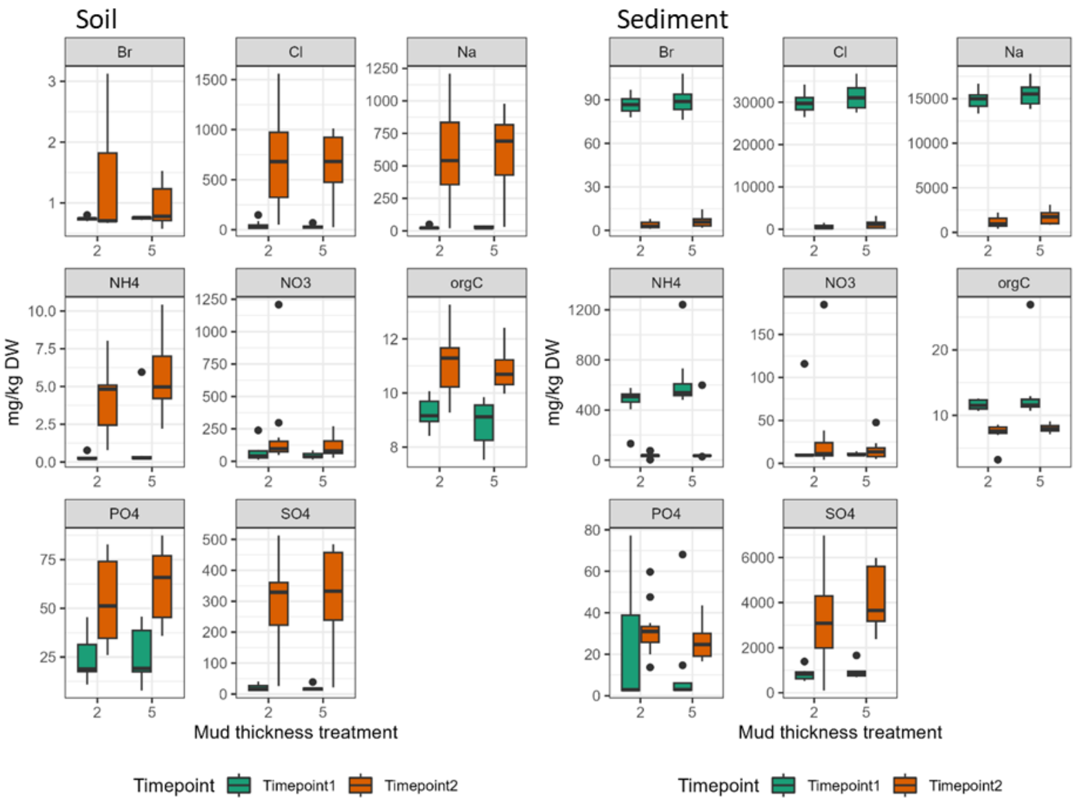


Figure 6.14: Concentration of bromide (Br), chloride (Cl), sodium (Na), ammonium (NH_4), nitrate (NO_3), organic carbon, phosphate (PO_4), and sulfate (SO4) in mg/kg dry weight (DW) for each plot, including both the sediment and soil underneath. In addition, the difference between the treatments of sediment layer is reported.

Figure 6.15 presents the salt (NaCl) concentration, expressed as gNaCl/L porewater, in both soil and sediment. This figure also compares two different mixing treatments: freshwater and saltwater. Initially, the sediment exhibits a high salt concentration, even when mixed with freshwater. The difference between these two treatments is only a few percentage points, suggesting potential discrepancies during the mixing process. It's worth mentioning that the evaluation of the mixture was reliant on expert judgement, which might have led to the observed similarity in salt content.

A key observation from Figure 6.15 is the decrease in salt content in the sediment, coupled with an increase in the underlying soil. This decrease in sediment can be attributed to the runoff and subsequent washout caused by rainfall, leading to the infiltration of salt into the soil. Variations in the salt content of the dike soil could influence its physical properties and strength. Therefore, specific analyses are required to evaluate these possible changes.

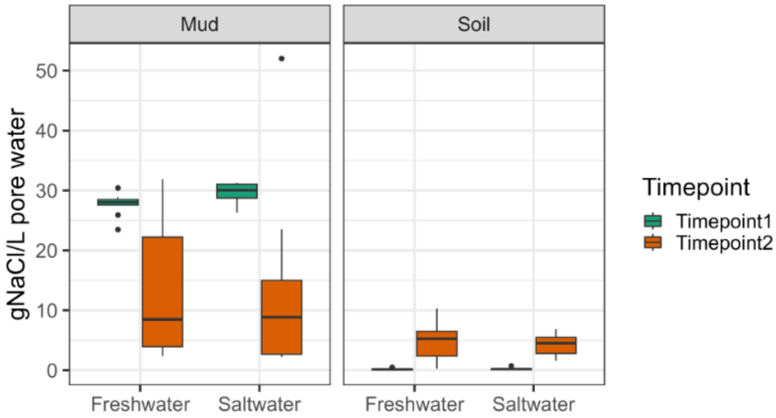


Figure 6.15: Salt (NaCl) content in the sediment and soil for the two mixing treatments at the beginning of the pilot and three months later.

In conclusion, the comparison of water content between sediment and the underlying soil at the beginning of the pilot and three months later is reported in Figure 6.16. The water content in both the sediment and soil decreased during the first three months of the pilot. The decrease was more pronounced in the sediment due to its direct contact with the air and the weather conditions during the initial months which facilitated the drying processes. The decrease in water content in the soil was less noticeable, and it was likely due to evaporation also resulting from the weather conditions that characterized the initial months of the pilot.

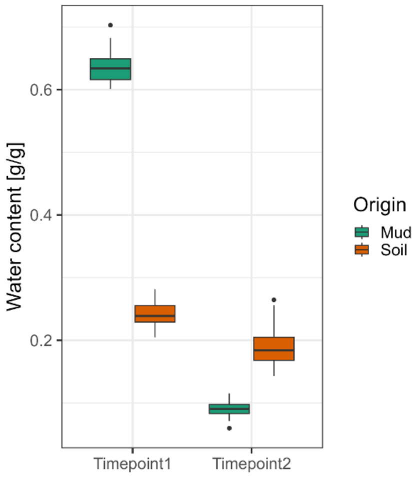


Figure 6.16: Water content in the sediment (mud) and soil for the two time points considered (i.e., at the beginning of the pilot and three months later).

6.3.2 Layer thickness development

Figure 6.17 and Figure 6.18 depict the development of sediment layer thickness during the first week of the pilot for the two thickness treatments and the three sub-areas of each plot, respectively. As previously detailed in section 6.2.4, these measurements were conducted using a ruler with precision of 1 cm. Measurements after the first week have been done with the SEB and the results are reported always in this paragraph.

Specifically, Figure 6.17 illustrates the average sediment layer thickness during the first week of the pilot for two distinct treatments: 2 cm and 5 cm. The initial thickness (on May 31st) for the 2 cm treatment was 5.08±1.6 cm, while for the 5 cm treatment, it was 5.89±1.61 cm. Demonstrating an evident decreasing trend over the first week, the thicknesses after six days (on June 6th) were 1.81±0.74 cm and 1.96±0.67 cm for the 2 cm and 5 cm treatments, respectively. Both treatments presented similar compaction, calculated as the difference between the initial and final thickness divided by the initial thickness. The 2 cm treatment showed a compaction of 64.5% after six days, while the 5 cm treatment demonstrated a compaction of 66.7%.

An initial observation regarding the sediment layer thickness development during the first week of the pilot is that the actual initial layer thicknesses significantly deviated from the intended values of 2 cm and 5 cm. This difference is particularly notable for the 2 cm treatment, which started with a layer thickness more than two times larger than the intended. As a result, the difference between the initial layer thickness of the two treatments did not represent the fact that two spraying rounds were performed only for the second treatment (5 cm). Specifically, the thicknesses after 6 days were very similar, effectively deleting the already modest initial difference.

Despite a clear decreasing trend observed during the first week after the application, attributable to the dewatering and compaction of the sediment on the dike, an unusual increase in thickness of approximately 1 cm compared to the previous day is noted after three days for both treatments. This increase is physically implausible, considering no additional spraying rounds were conducted. The potential sources for this inconsistency are identified: the limited precision of the measurement method and the inhomogeneity of the sediment layer. The anomalous thickness increment may be due to the 1 cm precision of the ruler used during the first week of the pilot, as evidenced also by the high standard deviation values characterizing all the measurements. Furthermore, since the measurements were not performed in precisely the same spots every day, the decreasing trend could be influenced by the inhomogeneity along the entire slope.

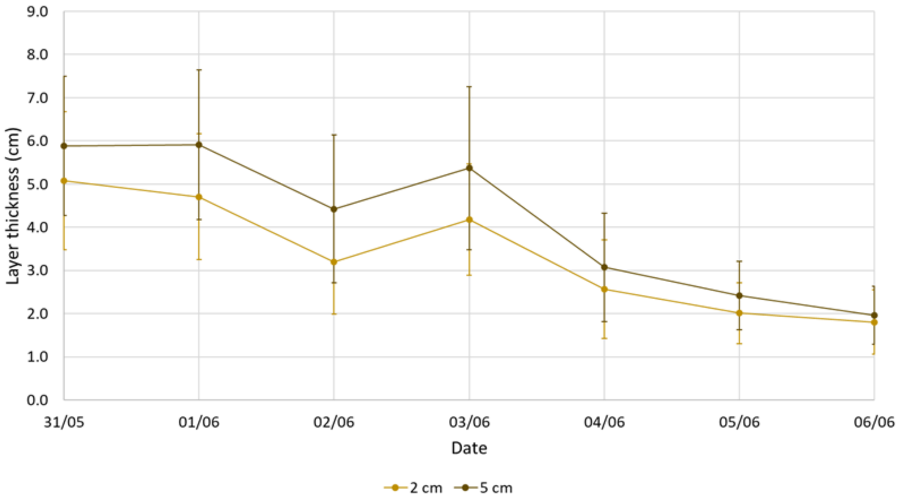


Figure 6.17: Average of the sediment layer thickness during the first week of the pilot for the plots with 2 cm and 5 cm treatments.

Figure 6.18 depicts sediment layer thickness development during the first week after application of the material averaged for the three sub-areas in each plot. The area at the bottom of the slope presented a higher initial sediment layer thickness with respect to the other two areas. The initial (31st of May) sediment layer thickness was 6.13±1.91 cm, 5.12±1.43 cm, and 4.92±1.25 cm for the bottom, middle, and high area on the slope, respectively. After six days (6th of June), the bottom area presented a layer thickness of 1.5±0.6 cm, while for the middle and high ones was 2.12±0.74 cm and 1.95±0.66 cm, respectively. Additionally, the three areas presented also different compaction during the first week of the pilot, with 74.7% for the area at the bottom of the dike and 59% for the middle and highest ones.

The initial layer thickness of the three sub-areas is different, showing the inhomogeneity of the sediment layer over the slope. The lowest area, at the bottom of the slope, presented the thickest sediment layer. The latter can be due to the flowing of the applied material from the higher parts of the slope to the bottom. This movement of material in direction of the bottom of the slope could be intrinsically exacerbated by the method used for applying the material. In fact, the material that already lay on the slope can be further pushed in the direction of the bottom of the slope by the ‘new’ (sprayed) material.

Although a distinct decrease of the sediment layer thickness for each sub-area during the first week of the pilot, an anomalous increment of approximately 1 cm happened between the second and third day. As already mentioned above, this variation from general decreasing trend, can be due to the low accuracy of the measurement method and inhomogeneity of the sediment cover over the slope. Even though the sediment layer thickness was higher in the area at the bottom of the slope, after six days the areas at the middle and top part of slope presented similar and higher thicknesses with respect to the bottom area.

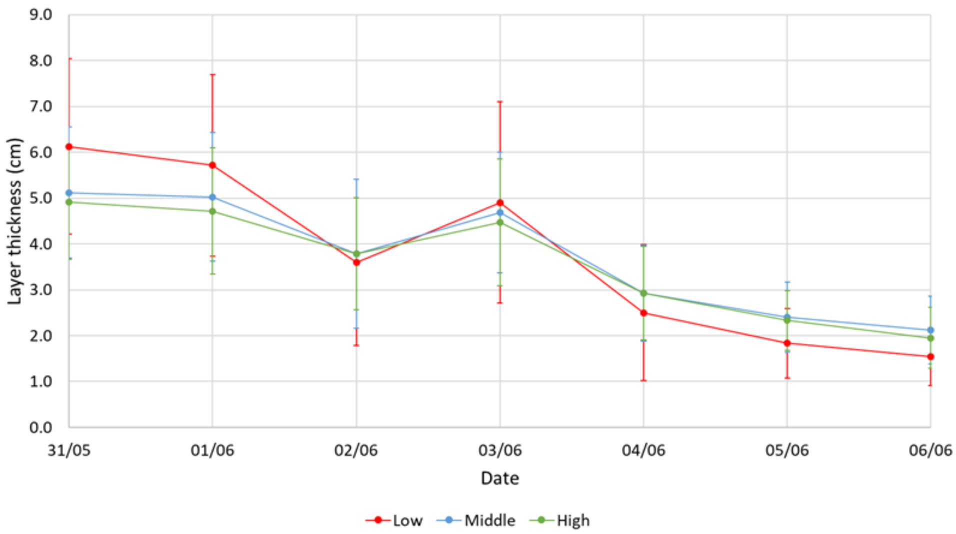


Figure 6.18: Average sediment layer thickness development during the first week of the pilot for the three sub-areas of each plot.

As already mentioned in section 6.2.4, the measurements for each sub-area of each plot of the initial sediment layer thickness served also for the estimation of the total volume of material applied on the dike. We determined the volume of the sediment applied over the testing area by considering the average initial layer thickness for each sub-areas and multiplying it for the area of each sub-area (a third of the total area of each plot). As a result, we obtained an estimation of the applied material in each sub-area and then, by summing all of them, we obtained the estimation for the entire pilot’s area which was equal to 80.2 m^3.

The kick-off of the Growing Dike pilot with the complete cover of each plot forming the testing area required the utilization of 11 tractors with slurry tank. Each of the latter can store 7 m^3 meaning that for the pilot we applied a total of 77 m^3. Although the ruler presented a precision of 1 cm, the estimation of the applied material is quite accurate when compared with the real amount of sediment utilized for the pilot.

Figure 6.19 shows the development of the layer thickness of the material applied to the crest of the dike after three months from the pilot's kick-off. Unlike the slope, less measurements and with lower frequency were conducted for the crest.

The actual initial layer thickness of 3.58±1.12 cm was more similar to the intended ones of 3 cm than that for the slope. After almost a month, the layer thickness was 1.97±0.81 cm indicating a compaction 45.1% from the application of the material. The compaction is smaller than the ones obtained for the sediment applied over the slope. The difference can be explained by the different periods in which the material was sprayed over these two parts of the dike. The material was applied on the slope and on the crest respectively on the 31st of May 2023 and on the 12th of September 2023. Different environmental and weather conditions can strongly affect the dewatering and subsequent compaction of the material.

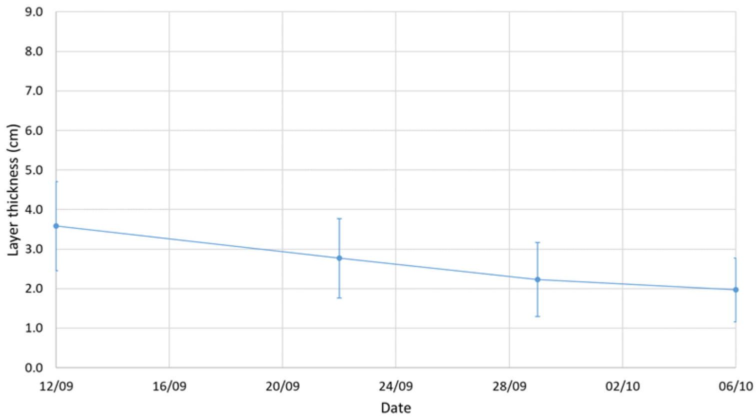


Figure 6.19: Average sediment layer thickness development during the first week after the application of material on the crest of the dike.

Figure 6.20 depicts the average layer thickness over time for both the layer thickness treatments measured with the SEBs. As already mentioned, the measurements with the SEBs started after 6 days from the beginning of the pilot in order to avoid perturbating the applied sediment. Six days after application the thickness of 2 cm layer treatment was 3.9±0.29 cm and 4.4±0.27 cm for the 5 cm layer treatment. Between the two treatments, there was no discernible difference (t_{39} = 0.55197, p = 0.58). Compaction was seen in both treatment layer thicknesses; for the 2 cm and 5 cm layer thicknesses, it was 46% and 39%, respectively. By the end of August, there was no discernible difference in the dredged material's thickness between the two-layer thickness treatments (t_{39} = 0.89047, p = 0.38). Compaction was shown to be significantly influenced by dike position (F_{39} = 3.535, $p < 0.05$), with the least compaction occurring at the most central location (Figure 6.20b). While there is a slight variation in the resulting layer thickness for each treatment (Figure 6.20a and Figure 6.20b), the difference between the treatments is not statistically significant (F_{35} = 2.02, p = 0.09). In March the layer thickness was only measured in transect 2 and 5. These transects showed little change in sedimentation compared to the September measurements (Fig, 6.18A). Also, in March there was no significant difference between the two treatments (t_{12} = -1.94, p = 0.094). There was also no significant difference in the dike position for treatment 2 and 5 (F_9 = 1.14, p = 0.36).

It should be noted that, the measurement performed with the ruler and with the SEBs on the sixth day of the pilot differ of around 2 cm for both the treatments. The difference can be explained by the different locations at which the measurements were performed. In fact, the measurements with the rulers were performed on the side while the SEBs were placed in the middle of each sub-area. Due to the necessity of stopping the spraying of sediment when the side of each sub-area was reached, the amount of sediment in the middle could be more compared to the side.

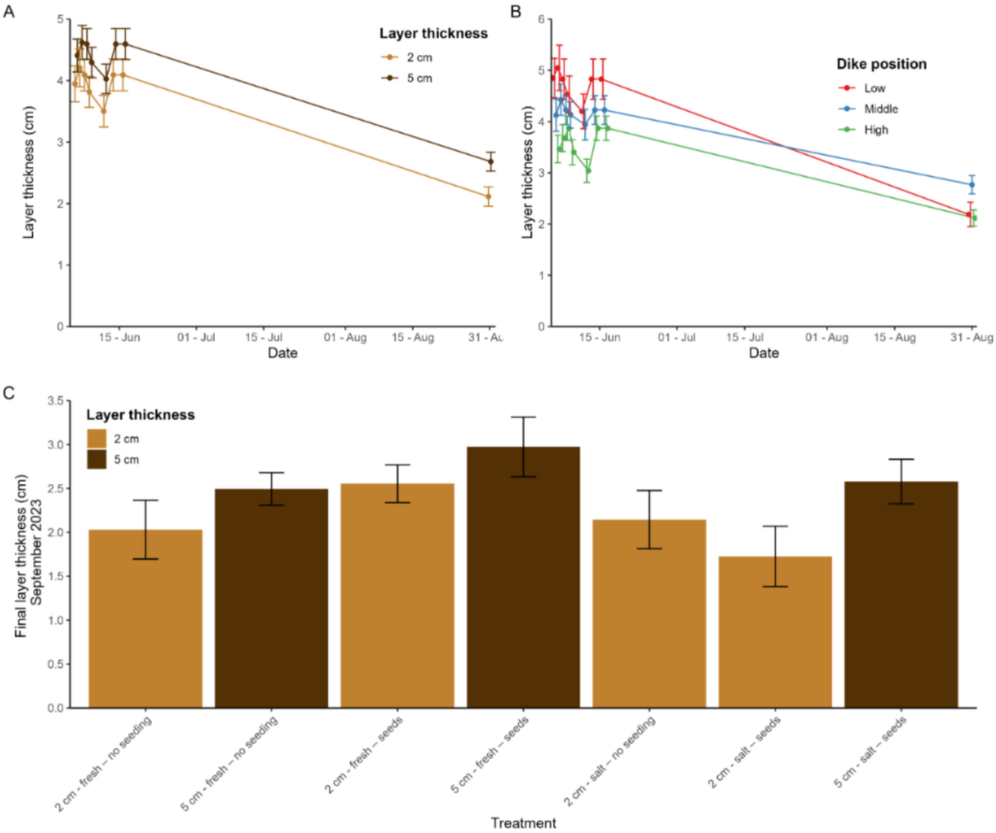


Figure 6.20: Average layer thickness over time for A) the 2 and 5 cm layer thickness treatment and B) dike position. C) Final layer thickness in September 2023 for each treatment. The measurement in March 2024 was only measured at transect 2 and 5.

6.3.3 Vegetation

Table 6.5: Percentages of species coverage during the pilot.

Latin name	23/05/2023	31/08/2023	21/03/2024
Grasses	42 plots	42 plots	12 plots
Lolium perenne	50% (42)	43% (42)	47% (12)
Festuca rubra	30% (42)	3% (40)	1.7% (9)
Agrostis stolonifera	30% (42)	2.7% (42)	1.4% (5)
Cynosurus cristatus	4.5% (32)	0% (0)	0% (0)
Bromus hordeacus	3.2% (42)	4.2% (42)	19% (12)
Elymus repens	1% (6)	1.1% (15)	0% (0)
Herbs			
Geranium molle	9.2% (42)	4.7% (42)	10% (12)
Trifolium repens	10% (42)	3.8% (39)	1.0% (9)
Achillea millefolium/Torilis nodosa	4.2% (42)	0.91% (29)	16.9% (12)
Sonchus arvensis	10% (1)	0.5 (23)	1.3% (7)
Cirsium avensis	2.9% (4)	4.8% (7)	2.3% (2)
Bellis perennis	2.5% (24)	0.6% (15)	0.5% (3)
Trifolium dubium	0.9% (12)	1.6% (7)	0% (0)
Taraxacum offininale	0.75% (6)	0.75% (18)	1.0% (6)
Cerastium fontanum	0.5% (39)	1.0% (37)	1.9% (12)

Prior to the pilot, the dike's flora was mostly made up of grass and had an average of 10.41±0.27 species per plot, making it rather species sparse. As reported in Table 6.5, the most prevalent species of grass covering the dike was *Lolium perenne*. There were herbs under the lower cover as well. The dike was mowed to a vegetation height of 13.5±1.7 cm prior to the application of the dredged material.

Much of the vegetation was buried because of the dredging material flowing over it when it was applied. The dredged material hardened and developed cracks when the water evaporated from it. The dredged material was too firm for the flora to grow through, so it mostly grew in the cracks. All the plots had a vegetation cover of between 97 and 100% prior to the application; three months later, the vegetation cover was between 40 and 75% (Figure 6.21). In March 2024 most plots had recovered, the vegetation cover was overall above 90% and almost all transects were not significantly different from the control plot. Only transect 2 was significantly different from the control, this transect had more bare ground. However, the top of the dike had not recovered, the vegetation cover was very low (~20%). The difference in recovery between the side of the dike and the top of the dike suggest that it is better to apply dredged sediment early in the growing season.

When comparing the 5 cm layer thickness treatment to the 2 cm layer thickness treatment in September 2023 and March 2024, the vegetation cover was noticeably less (September 2023: F_{38}=6.77, p = 0.01; March 2024: F_{44} = 8.98, p = 0.004) (Figure 6.21). But there was no correlation between the thickness of the resulting layer and the amount of vegetation (t_{40}=0.85, p = 0.40). It is likely not the layer thickness that inhibits vegetation regrowth, as there was no discernible change in layer thickness between the 2 and 5 cm layer treatments. Dredged material was applied twice over the dike with the 5 cm layer treatment, as opposed to just once with the 2 cm layer treatment. It is possible that more vegetation was buried with this additional layer, which would account for the reduced rate of vegetation regrowth.

Initially, the vegetation recovery seemed unaffected by the addition of seeds to the dredged material (September 2023: $F_{38} = 2.67$, $p = 0.11$). However, in March 2024 there was a small positive effect of adding seeds to the dredged material (March 2024: $F_{44} = 4.25$, $p = 0.045$). Adding seeds might possibly help vegetation recovery. The vegetation recovery was unaffected by diluting it with fresh or salt water (fresh/salt water: $F_{38} = 2.13$, $p = 0.15$). Moreover, the average species richness per plot (11±0.21 species) was comparable to the pre-pilot measurement. The species composition saw a slight shift; two grass species, *Festuca rubra* and *Agrostis stolonifera*, still had a very low cover, while *Lolium perenne* almost had almost fully recovered. The percentage of herbs and grasses in the pre and after-pilot measurements is comparable. In March 2024 measurement the percentage of herbs was relatively high in transect 2. Herbs might have a faster recovery from being buried by dredged sediment, due to the presence of aboveground stolons.

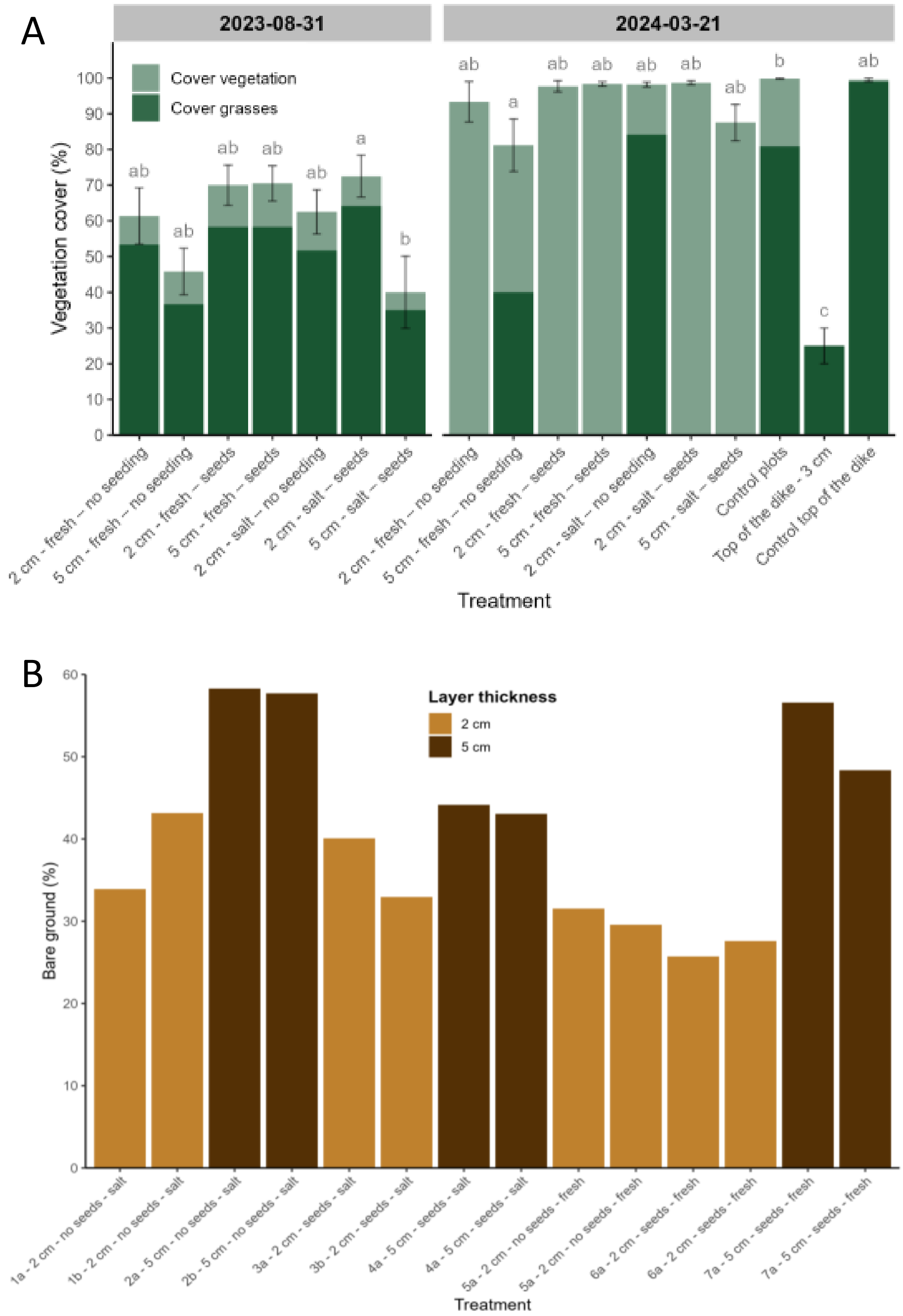


Figure 6.21: A) The percentage cover of the vegetation for each treatment in September 2023 and March 2024. Within the vegetation cover the proportion of the grasses is shown with a darker green colour. The error bars are only shown for the overall vegetation cover. In March 2024 the grasses cover is only measured for transect 2, 5, the control plots and the plots on top of the dike. B) the total bare ground cover in percentage for the whole section of dike in September 2023. The total bare cover is determined with the orthophoto.

Table 6.6: The rooting depth and number of roots. To measure the number of roots a classification has been used. 1 = 1 – 5 roots; 2 = 6 – 10 roots; 3 = 11 – 20 roots; 4 = 21 – 40 roots; 5 = >40 roots or a matting of roots. The grade is determined by the VTV method.

Depth	1A	1B	2A	2B	6A	6B	7A	7B	C1
0 - 2.5	3	3	5	4	4	5	4	5	5
2.5 - 5	2	3	3	4	3	4	3	4	5
5 - 7.5	1	2	2	3	3	1	2	4	4
7.5 - 10	1	2	1	3	2	4	2	4	3
10 - 12.5	1	1	1	3	2	2	1	4	2
12.5 - 15	1	1	2	3	1	2	2	2	3
15 - 17.5	1	1	2	2	1	2	1	2	3
17.5 - 20	1	1	1	1	1	1	1	1	3
Grade VTV	Very bad	Very bad	Bad	Moderate	Bad	Moderate	Bad	Moderate	Good

In September 2023, almost no new roots had developed in the dredged material. Though less in number than in the control plot, the deeper strata still contained roots from the original buried plant. Nevertheless, these data only provide an indication of the number and depth of roots because there were insufficient soil cores collected for each treatment. In the future, more soil cores will be required for an improved estimation. No root measurements were done in March 2024, however due to high vegetation cover it is assumed that roots have developed in the dredged material.

6.3.4 Greenhouse Gas fluxes

As previously explained in paragraph 6.2.6, GHG flux measurements with the MGGA were taken in relation to three specific dates throughout the pilot: prior to its starting, immediately after the application of sediment, and after three months. The measurements were conducted under specific environmental and weather conditions, particularly during the final measurements date which was on the 7th of September 2023. The processes under investigation and quantification, such as photosynthesis and oxidation of organic matter from the applied sediment, are highly sensitive to the prevailing environmental and weather conditions. These variables are linked to the period of the year during which the measurements were conducted. The temperature, sunlight, and wind, which can vary suddenly and locally, contribute to the natural variability in carbon dioxide uptake by plants and the GHG emissions from sediment rich in organic matter.

To determine the application method with the minimal carbon footprint, we examined the CO_2 and CH_4 fluxes from each testing plot. Thus, in the subsequent graphs, we depict the plots covered with material mixed with freshwater in light blue (1, 2, 3, and 4), while the plots filled with material mixed with saltwater in dark blue (5, 6, and 7). The reference plot, where no sediment was applied during the pilot, is marked in green.

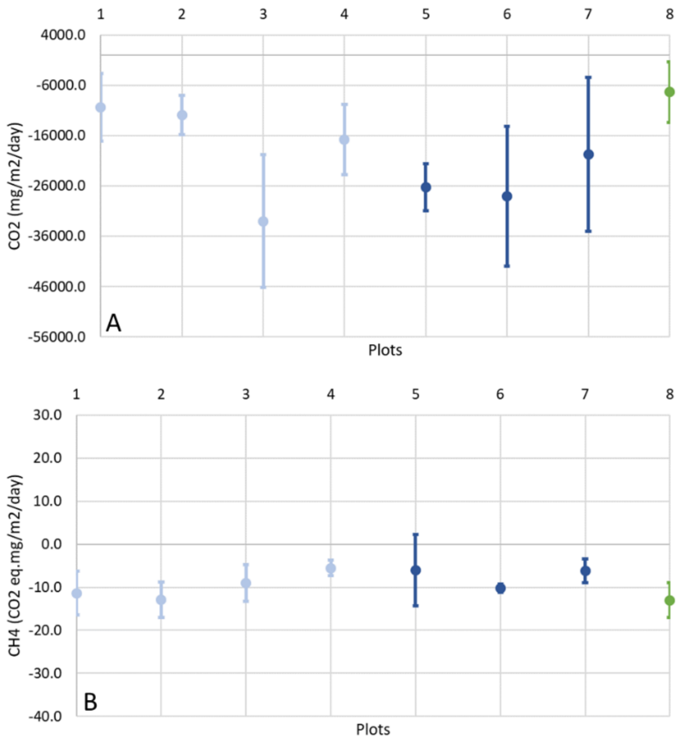


Figure 6.22: Fluxes of carbon dioxide (A) and methane (B) from the surface of the vegetated slope before the pilot kick-off for each testing plot (plot 8 corresponds to the reference). Plots where the sediment was mixed with fresh water are represented in light blue, while those mixed with saltwater are depicted in dark blue.

Figure 6.22 illustrates the carbon dioxide and methane fluxes before the kick-off of the pilot, originating from the same vegetated surface of the slope for each testing plot. Both CO_2 and CH_4 fluxes exhibited negative values, indicating the absorption rather than emission of these two gases.

Specifically, carbon dioxide fluxes ranged approximately from -7.000 mg/m^2/day and -33.000 mg/m^2/day. These negative values underscore the vegetation's role in absorbing CO_2 from the atmosphere and storing it in organic material (i.e., vegetational tissues). The substantial variability observed across the different areas of the slopes confirms the sensitivity of vegetational processes, such as the photosynthesis, to local environmental and weather conditions.

In contrast, methane fluxes, expressed as CO_2 equivalent, exhibited less variability compared to carbon dioxide, around zero and ranging from -5 mg/m^2/day to 13 mg/m^2/day. These values confirm the limited direct interactions between vegetation and methane in the short term.

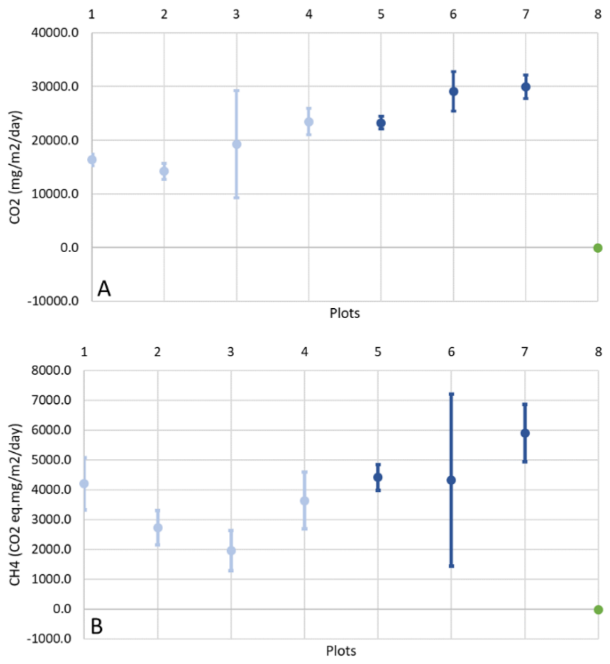


Figure 6.23: Fluxes of carbon dioxide (A) and methane (B) from the surface of the slope immediately after the application of sediment (plot 8 corresponds to the reference). Plots where the sediment was mixed with freshwater are represented in light blue, while those mixed with saltwater are depicted in dark blue.

Figure 6.23 depicts the fluxes of carbon dioxide and methane from each testing plot immediately after the application of the sediment. The slope was entirely covered by sediment, leading to the complete inhibition of CO_2 absorption by plants through photosynthesis. Consequently, both fluxes were positive, indicating the emission of CO_2 and CH_4 from the surface of the sediment applied to the slope. The fluxes from the reference plot remained consistent with those in the previous graph since no sediment was applied to that plot.

Carbon dioxide emissions ranged from approximately 14.000 mg/m^2/day to 30.000 mg/m^2/day for plot 2 and 7, respectively. An increasing trend bis visible between plots covered with material mixed with freshwater (in light blue) and plots with material mixed with saltwater (in dark blue). The average emissions ranged around 18.000 mg/m^2/day and 27.500 mg/m^2/day for the two treatments, respectively.

Methane fluxes, ranging from approximately 2.000 mg/m^2/day to 6.000 mg/m^2/day, were lower compared to the carbon dioxide. These values indicate that the contribution of methane emissions was smaller than that of carbon dioxide in terms of quantity, despite methane's greater impact in terms of the greenhouse effect. In fact, the global warming potential of methane is almost 30 times greater than that of carbon dioxide over a 100-year period (Myhre et al., 2013).

Figure 6.24: Slope three months later the beginning of the pilot. The surface exhibits heterogeneity, with patches characterized by varying degrees of vegetation cover, while others were solely covered by sediment.

Figure 6.24 illustrates sections of the slope three months later the pilot’s kick-off. The sediment layer applied was distinguishable, along with the vegetation that had grown through it over the preceding three months. The surface exhibited noticeable heterogeneity, with some patches solely covered by sediment and other more vegetated. To ensure consistency, we always positioned the MGGA in the same spots for each sub-area of every testing plot across all three measurement rounds throughout the entire duration of the pilot.

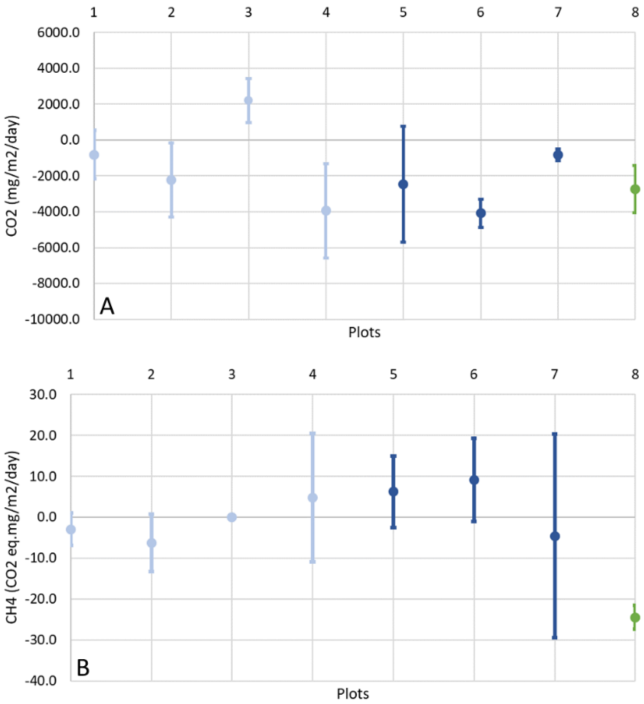


Figure 6.25: Fluxes of carbon dioxide (A) and methane (B) fluxes from the surface of the slope three months after the application of sediment (plot 8 corresponds to the reference). Plots where the sediment was mixed with freshwater are represented in light blue, while those mixed with saltwater are depicted in dark blue.

Figure 6.25 illustrates the carbon dioxide and methane fluxes from each testing plot three months after the kick-off of the Growing Dike pilot. These measurements were conducted in mid-September, characterized by different environmental and weather conditions compare to the end of May when the pilot kicked off. As a result, in analysing these data, we must consider the influence of the environmental and weather variables on both vegetational processes and emissions from the applied sediment.

Both CO_2 and CH_4 emissions experienced a decrease due to two primary factors: the growth of vegetation through the sediment layer, leading to the (re)starting of CO_2 absorption through photosynthesis, and the reduction of available organic matter within the sediment. Specifically, carbon dioxide fluxes became negative for almost all plots, ranging from 2.000 mg/m^2/day to -4.000 mg/m^2/day for plots 3 and 6, respectively. No significant differences were observed between the two treatments. Although the CO_2 fluxes were negative, they were still lower in absolute values than those observed before the start of the pilot (directly from the naturally vegetated slope). This can be attributed to the incomplete recovery of vegetation on the slope (as mentioned in paragraph 0 and showed in Figure 6.24) and the presence of patches with higher sediment cover.

Regarding methane, the fluxes decreased and became comparable to the initial levels. While some plots exhibited positive fluxes, there were no significant differences between the two treatments. Additionally, these results show that after three months the soil can even act as a methane sink in some cases.

Figure 6.26: Crest of the dike immediately after the application of sediment.

Figure 6.26 depicts the crest of the dike immediately after the application of the sediment on the 12th of September 2023. We measured the GHG emissions from the crest of the dike only once and immediately after the application of the sediment. The emissions were approximately 26.000 mg/m^2/day for carbon dioxide and 6.600 mg/m^2/day for methane. These values are both comparable to the emissions we measured immediately after application of the sediment on the slope.

7 Modelling the behaviour of sediment when applied on a dike slope

7.1 Introduction

The modelling approach was conducted in parallel with and after the application experiment and the pilot. The results obtained during the pilot could be used to get insights into the value of the modelling approach. Additionally, while trialling various application methods, considering fluid mechanics may help identify the most efficient application method. The application tests in the current project served as both a base and a demonstration of the interplay between non-Newtonian fluid mechanics and the possibilities of dike covering.

The primary objective of the modelling effort was to quantitatively assess the theoretical sediment layer thickness achievable through material spraying on the slope. This assessment is based on principles of mechanical equilibrium and fluid flow theory.

This chapter provides a theoretical background on the behaviour of applied material on a dike slope (section 7.2). Section 7.3 introduces the inputs for the model while an overview of the main steps taken in the modelling approach for the Lauwersoog pilot is presented in section 7.4. Lastly, section 7.4.2 presents the results of the modelling approach.

7.2 Theory of behaviour of soft sediment on a dike slope

For the application of sediment on a dike slope, several key properties must be considered:

1. Properties of the applied sediment
2. Properties of the dike
3. Spraying method

1. Properties of the applied material
The strength and flow properties of the sediment play a crucial role. When dealing with soft materials, their combined behaviour is referred to as rheology. Rheological properties in sediment-type materials originate from the colloidal aggregated structure of the clay platelets that bind with water. These materials can withstand a certain stress before transitioning into a flowing state.

Flow properties are typically described in terms of viscosity, but for non-Newtonian fluids like dredged sediment, viscosity is not a single value, and it varies with flow conditions. However, an exception is the so-called ‘plastic viscosity’ (as described by the Bingham model), which quantifies the increase in shear stress with rising shear rate, providing a more accurate depiction of the material’s rheology. Viscosity, defined as shear stress divided by shear rate, encompasses both strength and flow behaviour.

In flow situations, shear stresses are greater than the yield stress associated with the flow condition. Additionally, the material’s initial strength may exceed its strength under flow conditions due to internal adjustments over time.

The material stays and adheres to the dike primarily due to its strength, but there is a limit: layers cannot be thicker than what the sediment can self-support (internal stresses should not exceed the yield stress). The relationship between yield stress and viscosity is intertwined, governed by the internal structure of the clay matrix. Thicker layers can be deposited when the yield stress is high, but this also results in increased resistance to flow.

Time-dependent strengthening is another important factor, determining the interval during which sediment layers can be applied. Part of the knowledge applied within this modelling approach has been adapted from earlier research on industrial mine tailings deposition on beaches (Sittoni et al., 2019) and is now being applied in innovations in dike covering.

2. Properties of the dike

- Slope of the dike: The slope angle of the dike affects the equilibrium of sediment on its surface, with steeper slope experiencing greater gravitational effects.
- Friction of the vegetation cover on the material flow: In addition to sediment rheology, the texture (i.e., roughness) of the dike plays also a role. Although we primarily deal with laminar flow, roughness does not influence the laminated flow. Grass is likely flattened by the applied sediment cover and cannot function as “straws” to cling on.
- Lithological composition of the top part of the dike: The composition of the top part of the dike affects its texture, which, together with the vegetation cover, influences the friction experienced by the flowing material.

3. Spraying method

Encompassing various factors such tractor velocity, , nozzle type, inclination, and associated ‘spraying protocol’. Another application method could involve flow from a pipe located on top of the dike. In this project, the focus of the spraying method was on sediment application from a nozzle.

7.3 Model input: conditions and properties for the case at Lauwersoog dike

For modelling the behaviour of sediment on the dike slope at Lauwersoog, the following key properties were considered.

7.3.1 Properties of the applied material - Rheology

The rheological properties of sediment are crucial for its application and stability on the dike. The material is dredged from the harbour of Lauwersoog, located along the Wadden Sea. Part of the sediment is mixed with freshwater, while another part is mixed with saline water collected directly from the harbour.

A representative sample of the material sprayed on the dike was obtained from a batch pumped into the 7m^3 traveling slurry tank towed by the tractor. This specific batch was diluted with freshwater, and seeds were added. The material was subsequently applied to plot 3 and 4 on the dike. In the Physical Lab of Deltares (in Delft), the material was divided into several flat metallic cups. Samples diluted with freshwater were taken for rheometric measurement within approximately 3 minutes. Additionally, samples were placed in an oven to measure their water content.

Rheology was assessed using a Haake Mars I rotational viscometer, with a measuring element (vane FL 22) in cup CC Din 27. Two rheological measurements, labelled as “sprayed 1 & 2”, were conducted (see Appendix 10C.3), and their properties are as follows:

- W (mass water/mass solids) = 218 %
- Density = 1238 kg/m^3
- Static Yield stress (SYS): sample 1 = 68 Pa, sample 2 = 82 Pa
- Dynamic Yield stress (DYS): sample 1 = 39 Pa, sample 2 = 39 Pa
- Bingham yield stress (BYS): sample 1 = 57 Pa, sample 2 = 55 Pa
- Plastic viscosity (PV) = 0.2 Pa s
- Thixotropic behaviour: the sensitivity (SYS-DYS)/DYS exceeds 50%, indicating that the material exhibits thixotropic properties

Rheology was also measured at lower water contents obtained by placing the sediment in an oven to speed up evaporation. This drying process, lasting 5, 9, and 17 hours, is unrelated to the spraying interval. Power law relationships were identified between water content and rheological properties. Adjusting the water content allows control over material strength, influencing the thickness of the deposited layer.

Rheological measurements were also conducted on freshly dredged sediment directly from the dredging vessel. These results are also shown in Appendix 10C.3.

7.3.2 Slope of the dike

As shown in Figure 7.1, the dike slope is 1:3.

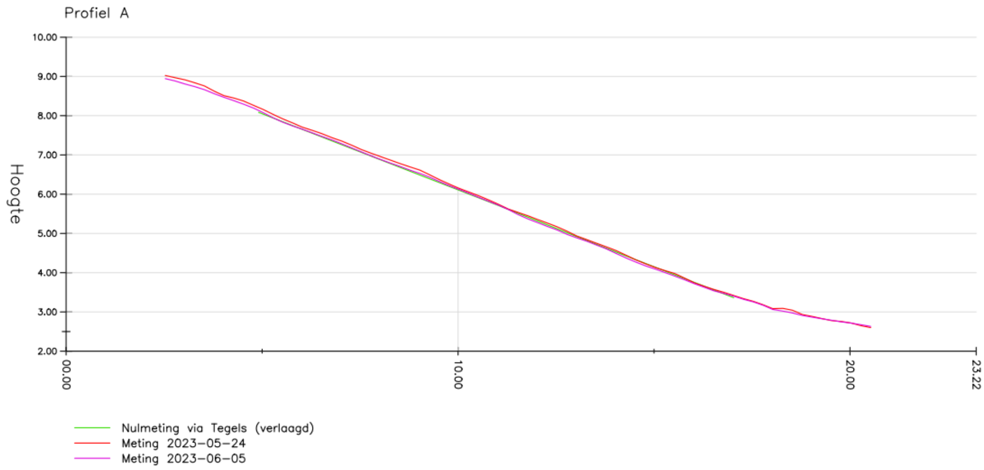


Figure 7.1: Vertical profile of the dike slope.

7.3.3 Resistance of the top part of the dike

The applied sediment will flat the vegetation, whereby the vegetation will not provide any additional hydraulic resistance. Laminar flow follows the contours of obstacles, such as rough surface and around grass pollens. In laminar flow, there are, by definition, no separation losses, like in turbulence. The rheological properties of the sediment layer are the decisive factor. The contribution of vegetation to resistance is minimal. In laminar flow, mainly contact area counts, which will increase minorly. Flow diverges around grass pollens, resulting in slightly wider lateral spreading. Soil characteristics are irrelevant to the application of the sediment layer.

7.3.4 Effects of spraying method on behaviour of flow of material

When sediment is sprayed from the nozzle and lands on the dike slope, it is expected that the remoulded properties become relevant, leading to a thinner layer than measured. These properties include dynamic yield stress (DYS), Bingham yield stress (BYS) and plastic viscosity (PV). Interestingly, despite jetting and splashing, the material may not have undergone sufficient shear. As a result, the unsheared strength (static yield stress) becomes more critical. Photos and videos of the spraying reveal a coherent jet (which is not disintegrated into a spray). Additionally, there is a discernible difference between material diluted with marine water and that diluted with freshwater, with freshwater-diluted samples exhibiting slightly higher yield stresses.

7.4 Results: analytical approach and parameterisation of case at Lauwersoog dike

This paragraph provides an overview of the analytical analysis applied to gain insights into the relation between material properties, flow, and material deposition. Explanations are provided on the insights required to parametrize the case study.

The objectives are:

1. Quantify the sediment layer thickness achievable on the dike slope by applying the mechanical equilibrium and fluid flow theory.
2. Demonstrate how the measured rheology properties of sprayed material can be utilized to calculate the dike covering and identify the critical parameters that influence this process.

7.4.1 Approach

There are analytical solutions available for determining the equilibrium depth of sediment cover on slopes, considering the material's rheology. Additionally, solutions exist for discharging from a point source. Initially, we explored the former. Subsequently, a series of point sources was added to simulate the spraying process during continuous linear movement (of the tractor). The following steps are explored in this context:

- Equilibrium (flow) depth
- The theoretical nose profile
- Transverse spreading
- Model choice and fitting
- Theoretical deposition curves

Equilibrium depth

The Newtonian fluid flow serves as an example of flow, like water, while clay-rich material exhibits non-Newtonian flow properties (such as Bingham plastic), resulting in an unsheared plug in the top part of the flow. The yield stress of the Bingham plastic approach is used to calculate equilibrium (flow) depth according to fundamental mechanical equilibrium, as schematized in Figure 7.2.

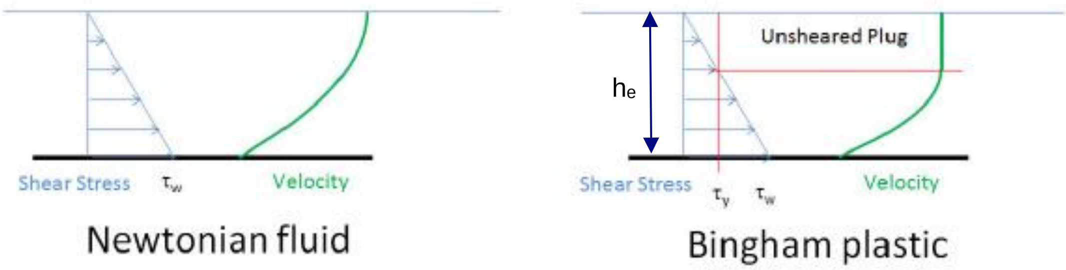


Figure 7.2: Plug near the free surface of open channel flow of yield stress fluid (Fitton Slatter 2013).

For static final equilibrium conditions, when τ_y equals τ_w and the velocity has vanished, the equilibrium depth is given by:

$$\boldsymbol{\tau_y = i\rho g h_e} \quad [7.1]$$

Where:

i = slope
ρ = mud density
g = gravitational acceleration

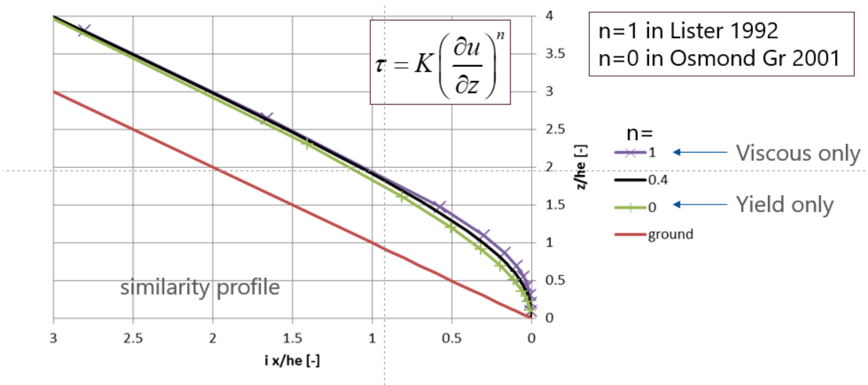
h_e= equilibrium mud depth, measured in vertical direction
τ_y = yield stress
τ_w = wall shear stress

For sprayed material on a dike slope with an inclination of i = 1:3, the theoretical depth of the sediment layer is approximately 0.01 m (at a yield stress of DYS=39 Pa). However, considering the static yield stress (SYS =75 Pa), the theoretical depth of the sediment layer becomes 0.02 m, aligning better with actual measurements.

At low flow velocities, an unsheared plug within the flow dominates and extends down to just above the bottom. Consequently, the bottom shear stress is only slightly higher than the yield stress. Using yield stress to estimate bottom shear stress is then a sound practise.

When discharging multiple layers on top of each other, it is crucial that the lower layer has gained strength in the meantime. Shear stress increment can result from thixotropy or dewatering.

Nose edge profile
The theoretical nose profile of material flowing down from a higher point is schematized in Figure 7.3.



Power law model: n=1 pure viscous, n=0: yield only (both analytical).

Figure 7.3: Nose profile of material flowing down from a higher point according to 1-dimensional theory.

For a power law model approximation of rheology (with n=0.088; see Appendix 10C.2), whether using the Osmond Griffith constant yield stress model (without plastic viscosity) or a power law rheology, a sediment layer thickness of 0.03 m corresponds to a nose profile length of 0.09 m. This effect is localized, impacting only a specific area rather than the entire system. However, it's important to note that the full equilibrium thickness is achieved within 0.1 m from the edge of the deposit.

Transverse spreading
The material, moving in a laminar jet, lands on the dike without losing its velocity, with its velocity estimated to be approximately 12 m/s. Despite this high velocity, which results in some splashing, we simplified the process by considering it as a discharge point for deposition calculations. This discharge point essentially travels along a straight line parallel to the dike crest. To further analyse it, we discretized this into discharges from a series of multiple point sources, each active for a short duration. The principle is illustrated in Figure 7.4. At each individual point, the sediment spreads both downward and transversally.

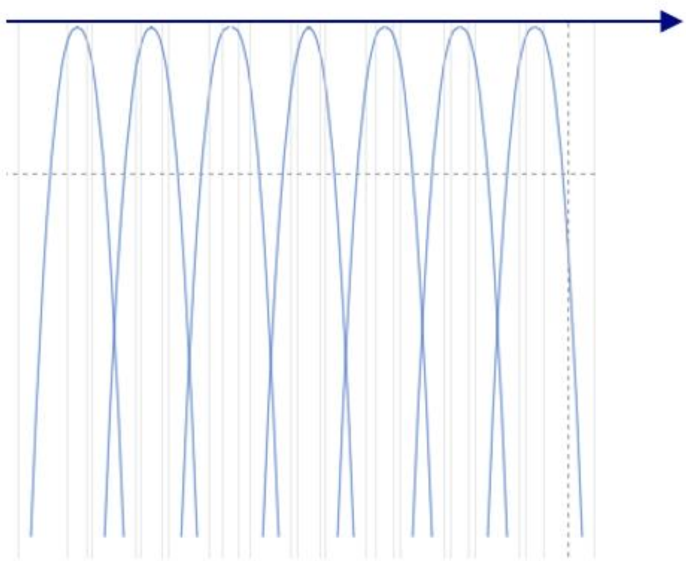


Figure 7.4: A series of point discharges simplifying the discharge from a moving source.

Theoretical deposition contours

Figure 7.5 illustrates the deposition contours of analytical models, considering various rheological models. The distances are normalized by the equilibrium depth (as per Eq. [1]) and the dike slope, denoted as i. h_0 represents the sediment thickness at origin, approximately equal to the equilibrium depth.

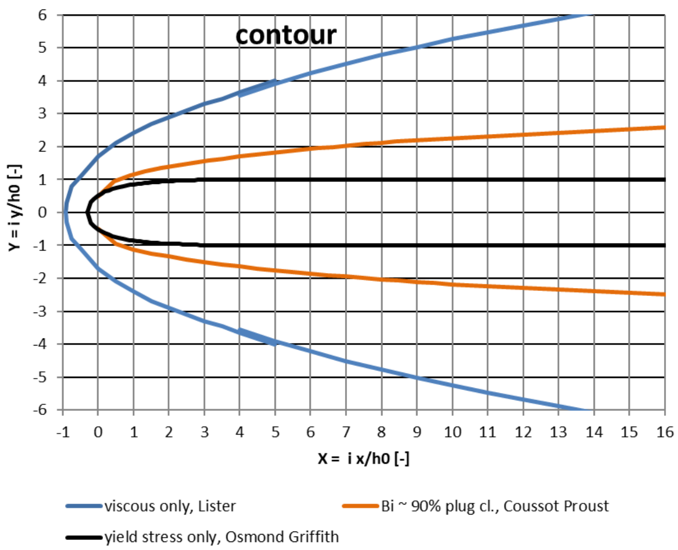


Figure 7.5: Deposition contours, h0 is mud thickness at origin (~equilibrium depth).

The deposited material naturally reaches mechanical equilibrium. Although the bottom shear stress is not exclusively directed downstream, its transverse component is balanced by the corresponding sediment surface slope.

The depicted solutions encompass components of the Bingham model:

$$\tau = \tau_y + K\frac{\partial u}{\partial z} \qquad [7.2]$$

Where:
K = plastic viscosity (PV)
du/dz = shear rate

When plastic viscosity is negligible (as in the Osmond Griffith model), an elongated deposit is expected, with the ratio of Osmond Griffith's initial depth (h_0) to the equilibrium depth (h_e) approaching 1. Figure 7.5 illustrates that for a dike slope of i=1:3, the width of the deposit is approximately 6 times its depth at the centreline.

In the case of entirely Newtonian viscous material (as described by Lister in 1992), a spreading behaviour with a power of 3/7 in the far field is expected (and a near-field solution with a power of 1/2). Notably, the flow conditions in Coussot Proust's work from 1996 indicate that approximately 90% of the flow consists of a plug-like behaviour.

Viscous flow
While analytical approaches exist, their dependency on velocity – such as viscosity - is not adequately represented. Furthermore, these analytical methods are limited to a single point source and non-accidented terrain. To achieve a more versatile and generic approach, the availability of a numerical code would be beneficial (an example is given in 10C.1). However, it is essential to recognize that analytical solutions remain crucial for verifying numerical calculations, and they serve as valuable tools for quickly performing feasibility studies and assessing ideas.

Model choice and fitting
Calculations (10C.2) revealed that Osmond Griffith solution, which neglects viscous behaviour, is unrealistic due to its slender deposit and high velocities. Therefore, the other extreme (i.e., viscous flow) was investigated. The contour in the far field is mathematically described by the equation below (see Figure 7.5, the blue contour line):

$$\boldsymbol{y = \frac{h_0}{i} 5.25 (X/10)^{3/7}} \qquad [7.3]$$

The footprint of the viscous solution (assuming 3/7 contour all the way to the origin) is given by:

$$\boldsymbol{A = (\frac{h_0}{i})^2 2 * 5.25 * 7 (X/10)^{10/7}} \qquad [7.4]$$

For a downstream distance of 6 m (corresponding to X = 200), the contour width is 0.5m. Considering a 2y distance, the tractor takes 3 seconds. The discharge volume ranges from 0.05 m^3 to 0.12 m^3. The higher discharge roughly corresponds to the volume of the applied material (2 cm thick): 6*1*0.02=0.12 m^3. A down-slope distance of 6 m covered in 3 s results in a flow velocity of 2 m/s, a more realistic scenario than the Osmond Griffith solution (Appendix 10C.2)

7.4.2 Recap of deposition modelling results
Based on fluid flow theory, sediment and dike properties, and assumptions regarding the spraying method, models were employed to calculate the sediment layer thickness. Using inputs from the Lauwersoog pilot, a layer thickness of 0.02 m was determined, generally corresponding to observed field thicknesses.

Insights into the spreading of the sediment after spraying are as follows:

- For an infinite-length flow-out from a point source, with an equilibrium depth of 0.02 m, Osmond Griffith's model predicts a width of 0.12 m. However, this results in a slender, stretched cover. As the material encounters grass pollens laterally, it may spread slightly wider.
- In a Bingham model approximation, with a dominant unsheared plug, the deposit width increases with distance, as described by Coussot Proust. At a flow distance of approximately 0.6 m (dimensionless distance 8), the width is expected to be 0.24 m.
- In a viscous Newtonian flow approximation, the width of the flow is approximately equal to the flow distance at 0.6 m.

Given the high velocities and relatively high flow rate, the viscous Newtonian flow approximation appears to be the most appropriate for the current spraying method. Despite the dynamics involved, the un-remoulded properties appear to be governing: the static yield stress (SYS) keeps the sediment layer in place.

By replicating the results from the field experiments with our models, we can better predict beforehand, how the material will behave in a different location (different dike composition) and with different material composition.

8 Conclusions

This report presents the results of the first implementation of the Growing Dike Concept (GDC). The research was conducted through a collaborative effort involving a large consortium with the waterboard Noorderzijlvest, constructor Klaei bv, Havenbedrijf Lauwersoog, Wageningen Marine Research, HAN – University of Applied Sciences and Deltares.

The project encompassed research into the application of freshly dredged material on a dike, with a specific focus on its role in contributing to water safety and potentially reducing greenhouse gas emissions. Small scale experiments were conducted, running in parallel with application experiments at the pilot site and modelling of material on a slope. In late May 2023, the pilot kicked-off, involving measurements and the filling of the different testing plots. Subsequently, monitoring measurements investigated the development of layer thickness, material properties, vegetation growth and recovery, and greenhouse gas fluxes.

Following the measurements, data analysis took place during Q3 and Q4 of 2023 and Q1 and Q2 of 2024.

The following chapter presents the answers to the main research questions addressed in Chapter 2.

8.1 Application method

Through the application experiment, we gained experience into achieving homogenous sediment layers by using different nozzles, adjusting its inclination, and varying the tractor speed. These experiments led to the development of a 'Spraying protocol' which consists into a set of instructions to follow to achieve a homogenous layer thickness over the slope.

The appropriate viscosity of the sediment was achieved by adding fresh or saltwater to the dredged material (in a ratio of 2:1 of dredged material and water). The decision on the appropriate viscosity was guided by expert judgement. Laboratory analysis of samples taken immediately after mixing revealed a water content total of 64% (referring to the total mass).

8.2 Dike management and reinforcement

GDC and water safety
In this paragraph the effects of the GDC on water safety (see section 2.3) are concluded.

Development of height
Regarding the development of height, compaction rate of the material from Lauwersoog reached approximately 65 % during the first 6 days. During both the small-scale experiment as during the pilot there was no rainfall which could cause dredged material to be washed away, so this effect could not be studied.

Critical flow velocity
Regarding the quality of the vegetation and the layer thickness, there was no correlation between the thickness of the resulting layer and the amount of vegetation cover after analysing the first data set (June – September 2023). In addition, the effect of adding seeds to the dredged material or diluting it with fresh water was not observed. This could be because the seeds were encapsulated by the fast-ripening process due to the weather conditions. There were no multiple layers applied so the affect could not be studied.

Shear strength of clay layer
In the time span of the application of the first layer the degree of cohesion could not be studied.

Moisture content of the topsoil (grass cover)
The effect of the dewatering process on the moisture content of the top layers is not studied in this phase. What became clear from the results is that the water content total decreased from approximately 64% to 25% in 5 days. Part of the dewatering could be by evaporation the other part could be contributing to the soil moisture content of the top layer.

Carbon cycle and GHG emissions
Investigating and quantifying GHG fluxes from both vegetation and sediment poses a challenge due to the high sensitivity of these processes to environmental and weather conditions. Temperature, sunlight, and wind, which can vary suddenly and locally, contributing to the natural variability in carbon dioxide uptake by plants and GHG emissions from sediment rich in organic matter.

GHG fluxes from the slope were measured at three different times during the pilot: before the kick-off, with no sediment applied, immediately after the application, and three months later. Consequently, our analysis is specific to distinct dates and environmental conditions, excluding vegetation respiration as measurements were conducted only during daylight.

One important insight gained from these analyses is the substantial impact that the application of sediment has on the carbon cycle, particularly on the GHG fluxes from the dike. In a 'normal' situation (i.e., before the pilot), the grass absorbed carbon dioxide from the atmosphere through photosynthesis, while large amounts of both CO_2 and CH_4 were emitted from the applied sediment. The vegetation was entirely covered, halting the uptake processes. Throughout the pilot, the vegetation grew through the sediment layer and large part of the organic matter initially contained in the material oxidized, causing a decrease of GHG emissions from the slope surface.

8.3 Sediment and vegetation development

Small-scale experiment
From the small-scale experiment, it can be concluded that for the two scenarios during the same time and weather conditions, it is seen that for an initial sediment thickness of 3 cm, the sediment layer thickness reduces with 70% within 6 days and maintains a constant thickness. For the scenario with an initial layer thickness of 6 cm, the sediment layer thickness reduces with 60% within 14 days before it reaches a constant thickness. The results of the sediment layer thickness reaching a constant thickness coincides with the water content evolution which also reaches the lowest measurements at the same time. The field tests occurred during a time frame where temperatures range between 9 – 20 °C with minimal precipitation. The organic matter content remained constant during the experiment. The initial mowed vegetation on the dike for both scenarios of tests recovered rapidly and was able to grow through the crack formation of the sediment layers.

Pilot
The pilot location has been setup to gain insight into the maturation of the dredged material and the development of the vegetation resulting from different layer thicknesses in a real case, the influence of fresh and saltwater, and the addition of seeds to the dredged material. For this purpose, 7 plots were defined in duplicate (totalling 14 testing plots), along with 2 reference plots on the slope. Each plot was divided into distinct sub-areas which were equipped with Sediment Erosion Bars (SEBs), tiles, and buckets.

The material dredged from the port of Lauwersoog is not contaminated and can be directly applied to the dike. The material consists of 7% organic material, with the remaining portion being inorganic. The particle size distribution includes a d50 of 17 μm, predominantly silt (75%), a small part of clay (4%), and the remaining fraction as sand (21%).
After mixing the dredged material with fresh or saltwater (2 dredged material: 1 water), it is transported to the pilot location and applied to the dike following the 'Spraying protocol' developed during the application experiment. The material is sprayed from the top of dike through a nozzle equipped at the back of the slurry tank by pressure. Then the sediment hits the slope of the dike, spreading due to the energy derived from the pressure tank and gravity force. However, due to the resistance of the vegetation, the material flows only for a short distance from the point of impact with the slope.

Sediment and soil chemical composition
Samples from both the soil and sediment were collected at the beginning of the pilot and after three months. These samples were analysed using Thermogravimetric Analysis (TGA) and Ion Chromatography (IC) to investigate whether the applied sediment alters the chemical composition of the underlying soil. Particularly, our analyses focused on:
- Quantitatively assessing the variations in the chemical composition of both the sediment and underlying soil
- Evaluating the impact of the applied sediment on the variations in the chemical composition of the underlying soil

The TGA analyses revealed an average water content total of 59%, 64%, and 24% for the freshly dredged sediment, applied sediment, and underlying soil, respectively. The organic content ranged between 6.6% and 8% for the freshly dredged sediment, and was 11.7% for the applied sediment, and 9.2% for the underlying soil.

The IC analyses enabled us to examine the chemical composition of both the applied sediment and soil at the beginning of the pilot and after three months. In addition to the TGA analyses, these further analyses allowed us to investigate temporal (during the initial three months) and spatial (between plots and treatments). Initial results indicated that biological variation exceeded variation between plots and treatments. Consequently, we chose to analyse only the variations between sediment and soil, averaging the data for the layer thickness treatments (i.e., 2 and 5 cm), and presenting the data as boxplots.

The results indicate the presence of runoff and leaching of ions from the sediment, with subsequent infiltration into the soil. This is particularly true for bromide, chloride, sodium, ammonium, and nitrate. A non-significant increase of organic matter in the soil was measured, which could be attributed to an increase of biomass growing through the applied sediment layer.

The results also show an increase in both phosphate and sulphate in the sediment and underlying soil. While the increase in phosphate and ammonium is likely due to mineralization of organic matter within the soil, the increase in sulphate in both the sediment and soil is probably the result of drying of the marine sediment, but it requires further analyses to clarify exchange dynamics between the two layers. In addition, the mineralization could be triggered by changes in the chemical composition of the environment following the application of the sediment.

Development of thickness of the layer
The reduction in thickness of the applied sediment layers is primarily caused by the dewatering and compaction of the dredged material. These physical processes lead to the maturation of the applied sediment into clay, forming a thinner layer on the dike. Throughout this pilot, two distinct theoretical layer thicknesses were applied and tested: 2 and 5 cm.

In both the small-scale experiment and the pilot, the most substantial decrease in thickness occurred within the first week after the material application. Regarding the pilot, compaction rate reached approximately 65 % during the first 6 days following the kick-off, attributable to the dewatering process. As a result, the water content total decreased from approximately 64% to 25% in 5 days.

The actual initial layer thicknesses were more similar than the intended ones, reflecting the challenge of achieving precise sediment layer thickness on an inclined surface. The 2 cm treatment started with an average thickness of approximately 5 cm, decreasing to 2 cm after three months. Similarly, the 5 cm treatment started with an initial thickness of approximately 5.9 cm, decreasing to around 2.5 cm after three months. After three months there was no change in layer thickness. Despite a slight variation in resulting layer thickness for both treatments, the difference is not statistically significant.

The digital surface model includes the vegetation height, this caused the elevation following the application of the dredged material to be lower than the initial elevation including vegetation, because the vegetation was buried by the dredged silt. The digital surface model might be helpful for long-term elevation changes (such as those that occur over several years), but it is not suitable for short-term elevation changes.

Evaluation of modelling behaviour of sediment development on a dike slope
The characteristics of the material, the spraying method, and the dike’s geometry (excluding the vegetation) served as input parameters for the model used to estimate the theoretical thickness. This calculation resulted in a layer thickness of approximately 2 cm. Assuming that the material is remoulded during spraying, the static yield stress allows a mud thickness of 0.02 m to remain stationary.

Rheometry shows that the material is thixotropic i.e. gains strength at rest, meaning that it can stand higher strains. How fast this process proceeds are not known. Dewatering will also strengthen the mud. Power law relations are found between water content and rheological properties. Rheology is sensitive to water content, hence a small decrease in water content will make the material stronger, and thicker layers can be deposited.

Deposition occurs relatively fast. Fully viscous flow behaviour (where yield stress is negligible) is more likely than flow dominated by yield stress. The yield stress is though governing final deposit thickness. The analytical models are applied for both of these extremes.

The sprayed material will strengthen on the dike. The strengthened base created by the previous application must be able to support the new charge of material. We have information about rheological properties at different water contents. Change of water content in time can be calculated by a consolidation model. Thixotropic strength grow rate will have to be measured by means of rotational viscometry.

Development of vegetation
Prior to the pilot, the dike's flora was mostly made up of grass. Much of the vegetation was buried because of the dredging material flowing over it when it was applied. The dredged material hardened and developed cracks when the water evaporated from it. The dredged material was too firm for the vegetation to grow through, so it mostly grew in the cracks. After three months the vegetation cover was 40 – 75%. After 9 months, the vegetation had mostly recovered, generally the vegetation cover was above 90%. The vegetation cover on top of the dike had not recovered, indicating that applying dredged material should be done in the beginning of the growing season.

There was no correlation between the thickness of the resulting layer and the amount of vegetation. It is likely not the layer thickness that inhibits vegetation regrowth, as there was no discernible change in layer thickness between the 2 and 5 cm layer treatments. Dredged material was applied twice over the dike with the 5 cm layer treatment, as opposed to just once with the 2 cm layer treatment. It is possible that more vegetation was buried with this additional layer, which would account for the reduced rate of vegetation regrowth.

Adding seeds to the dredged material seems to have a small positive effect, with seeds present in the dredged material the vegetation recovery was slightly faster. However, this most likely depend on the plant species in the seeds mix. The vegetation recovery was unaffected by diluting the dredged material with fresh or salt water. Moreover, the average species richness per plot was comparable to the pre-pilot measurement. The species composition saw a slight shift; two grass species, *Festuca rubra* and *Agrostis stolonifera*, still had a very low cover, while *Lolium perenne* almost had almost fully recovered. The percentage of herbs and grasses in the pre- and post-pilot measurements is comparable.

After three months (September 2023) almost no roots had developed in the dredged material. The presence of roots was not measured after nine months (March 2023), however due to the high vegetation cover, it can be assumed that the roots developed in the dredged material.

Vegetation recovery progressed notably faster in the small-scale experiment conducted at Deltares compared to the large-scale experiment, the difference could be caused by multiple factors. Firstly, the vegetation composition was different, with herbs having a high cover compared to grasses in the small-scale setting. These herbs might possess better capabilities for penetrating the dredged material than grasses, thus affecting the recovery pace. Secondly, there was a difference in dike height and slope. The small-scale experiment featured a lower dike, which was not south-facing like the larger dike in Groningen, thus experiencing differing wind exposure. This dissimilarity in wind exposure might lead to discrepancies in soil moisture levels, potentially explaining variations in vegetation recovery. Thirdly, the small-scale experiment was conducted two weeks prior to the large-scale experiment. It took place at the onset of a dry period, potentially resulting in higher initial soil moisture levels.

Overall, vegetation recovery appeared to be influenced by factors such as vegetation composition, dike slope, angle, height, and prevailing weather conditions. Consequently, making generalized assumptions regarding vegetation recovery may not be feasible.

9 Noorderzijlvest criteria and follow-up

This chapter presents the discussion and findings on the main criteria addressed in the pilot at Noorderzijlvest, the evaluation of these criteria, and the proposed follow-up. These were also partly described in a memo [4] that was used in a go/no-go decision on the 16th of January for the pilot at Hoogheemraadschap Rijnland within the HWBP Meegroeidijk proposal[5]. The decision was made to proceed with the pilot at Hoogheemraadschap Rijnland.

The consortium notes that many practical things have been learned at Noorderzijlvest, which will be useful for the follow-up and for other pilot locations. However, the impact of the GDC in the short and long term is not yet fully known because only one sediment layer has been applied and has not yet been monitored for a full year. The described points of attention and improvement, described in the table below, must be included in follow up plans for the coming years.

Criteria Noorderzijlvest 2022-2023	Judgement	Points of interest translated into other pilots and follow-ups
Can you apply the sediment homogeneously in thin layers?	A single thin layer can be applied homogeneous. During the field experiment, experience was gained in setting up layers on a dike slope. These experiences have been included in a "spraying protocol" for covering the pilot at Noorderzijlvest.	In the Noorderzijlvest pilot, it was possible to adjust the viscosity by adding water (2 parts of sediment and 1 of water) according to the dike's characteristics. If this is not possible, numerical modelling and lab tests can help estimating the application and layer thickness.
Can you apply the sediment in layers of 2 and 5 cm thick on a dike slope?	The results showed that there was no significant difference between the 2 cm and the 5 cm layers: both were approximately 5 cm thick after the application. In this case, to apply a thicker layer, it was decided to do this in two spraying rounds. In general, applying layers of sediment on a slope depends on the properties of the material, the slope of the dike and the resistance of the vegetation.	To determine the desired thickness of the layer for the pilot, insights into the sediment properties, the slope, and the resistance of the vegetation are required.
Does the applied layer remain in place well?	Yes	The composition of the sediment, the expected period of drying (partly depending on the weather conditions) and the chance of certain parts being washed out are important for this. There was very little rain during and after the Noorderzijlvest pilot. It is recommended not to start the pilot if a lot of rain is expected in the following 2 weeks.

[4] Oplegnotitie ten behoeve van Go/No Go pilot Rijnland (January, 9th 2024)
[5] Doornenbal et al. Voorstel Meegroeidijk. Waterveiligheid door gebruik maken van het meegroeidijkconcept. Rapport 11208659-000-ZKS-0001. September 2023.

Is the vegetation (re-)growing and developing after the application of the sediment?	After three months there was 40-75% recovery of the vegetation. After nine months the vegetation had almost everywhere recovered. The timing of the application of the dredged material is important, due to the long recovery time, it is best to apply dredge sediment at the beginning of the growing season. It is expected that the ripened material will be further absorbed into the dike due to rain, frost and vegetation growing through it.	For the Noorderzijlvest pilot, it was concluded to carry out 1 application round per year to provide the vegetation with the opportunity to recover. It is expected that the vegetation will recover better/faster in the Rijnland pilot due to the more favourable silt properties.
Does the sediment mature sufficiently in the first 8 months?	The material at Noorderzijlvest had the greatest ripening, especially in the first weeks. Geotechnical properties will be tested in a later phase. The TGA and IC analyses provided a snapshot of the chemical composition of the applied sediment and soil at the beginning of the pilot and after three months. The results confirmed the expectations: the addition of sediment, which is rich in salt and organic matter, led to the infiltrations of ions into the underlying soil affecting its composition.	It is expected that when the starting material (for instance at Rijnland) has a higher organic matter content, the effective filling will be less. This should be considered in the design. To further quantify and elucidate how ions are washed out from the sediment and infiltrate into the soil, additional analyses are required. Particularly, we suggest investigating: - The chemical composition of sediment and soil at intermediate timesteps - The depth to which ions infiltrate into the soil - The timescale over which the soil recovers and returns to its initial chemical composition
Are the chosen monitoring methods adequate?	Yes, height measurements with folding ruler, sedimentation erosion bar (SEB) and drones have been carried out. Each measurements technique has its advantages and disadvantages. Depending on what resolution is needed, how often the measurement needs to be repeated and whether the area needs to be covered, the right measuring method can be chosen. Yes, the vegetation measurements, both manual and classified with the drones, provided an accurate picture of the development of the vegetation. Regarding roots penetration into the soil underneath, an action plan will have to be drawn up in consultation. Yes, the properties of the sediment, depending on which parameters need to be analysed and with which frequency, can be evaluated through lab analysis.	Creating the correct layout of the pilot is important so that the measuring points are easily accessible. If we want to look at the prevention of crack formation and possible softening of the barrier, we must measure deeper than the top layer (namely the phreatic line about 50cm below ground level). For the Rijnland pilot, it is important to monitor the moisture content of the top layer, water levels and precipitation. Specific tests regarding the adhesion of applied material to the dike can be carried out at the end of the project.

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A Uitgevoerde fasen

Fase 0, 1 en Fase 2A zijn inmiddels uitgevoerd en afgerond. Hieronder zijn de activiteiten, conclusies en resultaten van deze fasen kort samengevat.

A.1 Fase 0

Binnen Deltares is het concept uitgewerkt en gereed gemaakt voor presentatie aan EcoShape.

A.2 Fase 1

De eerste Fase is uitgevoerd in 2020 en 2021 . In deze Fase is met bureaustudie de technische en financiële haalbaarheid van het concept geanalyseerd en het traject om te komen tot (grootschalige) uitvoering geïdentificeerd. Een generieke vergelijking met de kosten van reguliere dijkverbeteringsprojecten is gemaakt op basis van kentallen. Dit leidde tot het rapport “Meegroeidijk uitvoerings- en opschalingsplan” (EcoShape report, juli 2021).
Tijdens deze eerste Fase is dus een eerste beeld van de technische en financiële haalbaarheid onderzocht.

Conclusies Fase 1:

✓*GDC is:*

- ❖ *Financieel haalbaar / interessant*
- ❖ *CO2 verlaging vergeleken met traditionele standard praktijken*

✓*De GDC is goed verbonden met lokale en nationale doelen en initiatieven*

✓*Start met een pilot of kleine schaal, gefocust op de optimale uitvoering en onderhoud van het concept*

✓*Focus hierbij op:*

- ❖ *Karakterisering en gedrag van het materiaal op de dijk*
- ❖ *Interactie tussen het slib en de vegetatie*
- ❖ *De gevolgen voor dijkveiligheid*
- ❖ *Verbinding tussen het veld, lab en numerieke modellen*

A.3 Fase 2A

Op basis van de positieve resultaten van deze eerste Fase is door de partners besloten om door te gaan met de tweede Fase, waarin drie pilots ontwikkeld zijn bij de waterschappen: Waterschap Noorderzijlvest (pilot 1), Hoogheemraadschap Rijnland (pilot 2) en Waterschap Brabantse Delta (pilot 3). Daarmee wordt voldoende dekking bereikt van de condities zoals die in grote lijnen bij de primaire dijken in Nederland voorkomen. De variatie in de pilots maken de ontwikkeling van generieke kennis en aanbevelingen haalbaar.
Fase 2 is opgesplitst in drie delen. In 2021 en 2022 is gewerkt aan Fase 2A, waarin de focus lag op de voorbereiding van pilot 1 bij het Waterschap Noorderzijlvest (inclusief de aanvraag voor TKI subsidie) en het uitvoeren van de businesscases specifiek voor het Hoogheemraadschap van Rijnland (Horstman, .M, 17 augustus 2022) en het Waterschap Brabantse Delta (Horstman, M., 29 Juni 2022); deze businesscases zijn inmiddels afgerond.
Ook is een experimentenserie ontwikkeld door HAN, en projectfinanciering verworven bij KIEM met als financier het regieorgaan SIA.

TKI-project bij Noorderzijlvest
✓Projectplan opgesteld, locatie + aanpak opbrengen + eerste monitoringsplan bepaald
✓Onderzoekspartners samengebracht en werkverdeling bepaald
✓Opstart van methodiek voor het aanbrengen van sliblagen, aanleg proefstroken vanaf 1 mei 2023

Experimentenserie HAN
✓Projectplan opgesteld en locaties vastgesteld
✓Uitvoering vanaf voorjaar 2023, deels bij pilot Noorderzijlvest, deels lab

Business cases in Rijnland en Brabantse Delta
✓Uitgevoerd door RHDHV
✓Slib aanbod versus slib vraag op de pilotlocaties is geëvalueerd
✓Financiën van traditionele uitvoering versus GDC

Conclusies:
✓Kosten voor transport > kosten voor aanbrengen slib GDC (BD)
✓Vermeden kosten - voor afvoer slib, bij GDC aanzienlijk (BD)
✓GDC levert besparing op t.o.v. afzonderlijke bagger- en versterkingsopgave (RL)
✓Grotere laagdiktes - 10cm versus 2cm, leidt tot aanzienlijke toename transportbewegingen (RL)

B Contribution to International and National missions

The implementation of the GDC, once it has been scaled up from regional to national level, can contribute to the ‘Knowledge & Innovation agendas of the Top Sectors’ (https://www.topsectoren.nl/visiesvoordetoekomst), EU ambitions (such as Horizon Europe Framework and the Green Deal), and to International agreements (e.g., Paris Agreement), with the overarching goal of pursuing the UN SDGs.

Specific to the Netherlands, the Growing Dike is relevant for the following missions:

- Reducing national greenhouse gas emissions by 49% by 2030, toward a 95% reduction by 2050 compared to 1990.
- Achieve a sustainable and fully circular economy in 2050, with halving the utilization of raw materials by 2030.
- The Netherlands will be climate-proof and water-robust by 2050.
- Achieve a sustainable balance between ecological carrying capacity and water management vs. renewable energy, food, fishing, and other economic activities. This balance must be in place by 2030 for marine water environments and by 2050 for rivers, lakes, and estuaries.
- The Netherlands is and will remain the best protected and liveable delta in the world, with timely, future-proof measures at manageable costs.

In the government's policy framework, the last mission of the aforementioned list holds particular relevance for the Growing Dike (https://www.rijksoverheid.nl/documents/publicaties/2019/04/26/missions). The following ambitions have been formulated for this purpose:

- Earthworks for water-related tasks are energy neutral and their costs per m^3 have fallen significantly between 2020 and 2030. There is a healthy sediment economy by using, among other things, the Building with Nature concept.
- The replacement and renovation of water-related structures is energy neutral, circular and cost-effective, including through functional and technical lifespan-extending measures.
- Supplementary for the Flood Protection Program (HWBP): the ambition is to carry out dike improvements two times faster and 30 to 40% cheaper (per kilometer) compared to traditional works. In particular, the cross-project exploration of Dikes with Area-specific Soil (POV-DGG) examines the useful application of area-specific material in dike reinforcements to achieve the HWBP goals.

In addition, four missions are relevant specifically for Europe:

- Adaptation to climate change including societal transformation.
- Healthy oceans, seas, coastal and inland waters.
- Climate-neutral and smart cities.
- Soil health and food.

Contribution to international and national missions

The application of the GDC, once it has been scaled up from regional to national level, can contribute to the missions of the Knowledge & Innovation agendas of the Top Sectors (https://www.topsectoren.nl/visiesvoordetoekomst), European Missions (Horizon Europe Framework - https://ec.europa.eu/info/horizon-europe/missions-horizon-europe_nl#what) and to international agreements (Paris Agreement and UN SDGs).
Four missions are relevant specifically for Europe:

- Adaptation to climate change including societal transformation.
- Healthy oceans, seas, coastal and inland waters
- Climate-neutral and smart cities
- Soil health and food

Specific to the Netherlands, the GDC is relevant for these missions:

- Reducing national greenhouse gas emissions by 49% by 2030, towards a 95% reduction in emissions by 2050 compared to 1990.
- A sustainable and fully circular economy in 2050, with halving of raw material use by 2030.
- The Netherlands will be climate-proof and water-robust by 2050.
- A sustainable balance between ecological carrying capacity and water management vs. renewable energy, food, fishing, and other economic activities. That balance must be in place by 2030 for marine waters and by 2050 for rivers, lakes and estuaries.
- The Netherlands is and remains the best protected and liveable delta in the world, with timely, future-proof measures at manageable costs.

In the government's policy framework, the last mission in this list is the most relevant for the GDC (https://www.rijksoverheid.nl/documents/publicaties/2019/04/26/missions). These ambitions have been formulated for this purpose:

- Earthworks for water tasks are energy neutral and costs per m3 have fallen significantly between 2020 and 2030. There is a healthy sludge economy by using, among other things, Building with Nature concepts.
- The replacement and renovation of wet structures is energy neutral, circular and cost-effective, including through functional and technical lifespan-extending measures.
- Supplementary Flood Protection Program (HWBP): The ambition is to carry out dike improvements 2x faster and 30 to 40% cheaper (per kilometer) than in the past. In particular, the cross-project exploration of Dikes with Area-specific Soil (POV-DGG) examines the useful application of area-specific material in dike reinforcements to achieve the HWBP goals.

How the GDC contribute to water safety issues (in general, not only in NL):

- The reason we are focusing on vegetation and dike heights (and strengthening it)
- For water safety, there should be vegetation on the dike because it decrease the flow velocity (it doesn't reach the critical flow velocity)
- From Pieter slides

C Appendix modelling

C.1 Numerical

Numerical calculations might be possible with the Delft3Ds model (Sittoni et al., 2016: Talmon et al., 2018). It is having the non-Newtonian Rheological models, and sand settling. This sand settling appears not necessary for dike deposition and can be switched off. The model has been applied to gentle sloping beaches (Figure 10.1). Delft3D is not developed for steep flows, but it would be interesting to give it a try.

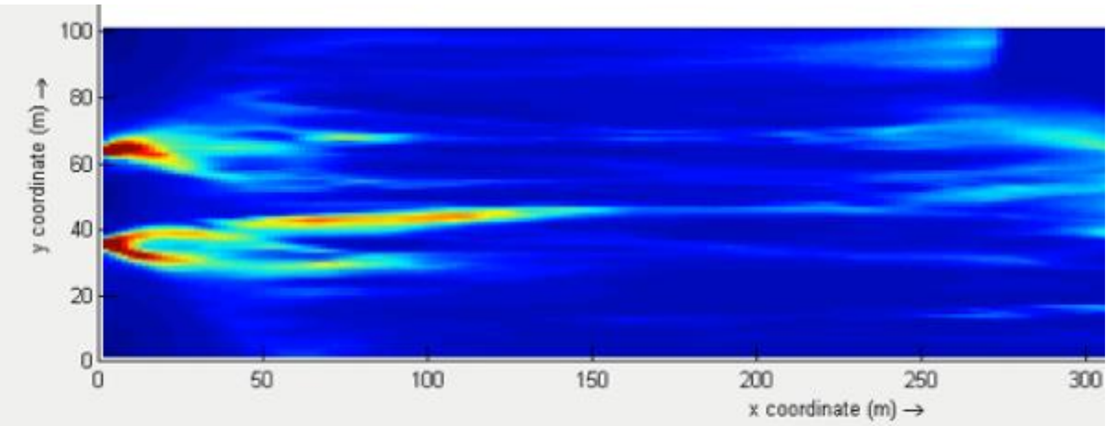


Figure 10.1: Two pipes discharging a sand-water-clay mixture over a 1:100 sloping beach.

If that won't work, the 2-dimensional (depth & length) research model applied in Talmon and Meshkati 2023 could be an alternative. It particularly focusses on detailed time-dependent rheology.

C.2 Yield stress only solution (Osmond Griffith)

With h_0=0.02 m the width of the deposit is 0.12 m. With a travelling velocity of the tractor of 0.3 m/s, this corresponds to an exposure time of 0.4 s. So, if we discretize the traveling in discrete unit steps of 0.12 m interval need to make to just cover the dike. In the 0.4 s the discharged volume is 0.0068 m^3 to 0.0168 m^3. Assuming a rectangle shaped 0.02 m height cross section, this corresponds to a run-out distance of 2.8 m to 7.8 m. (flow velocities would be 7 to 7.5 m/s in this solution, which is too high, and the plug would disappear: and a Newtonian viscous flow would result). For the low flow rate, it would suffice to cover the dike utilizing 3 different spraying distances.

C.3 Rheological measurements

C.3.1 General

Rheological measurements were conducted in duplo. Only the first measurement is analyzed for trends and quantification. First and second measurement are highly similar.

There are three relevant yield stresses, Talmon et al. 2023:
SYS = Static yield stress (= shear stress at failure of the material)
DYS = Dynamic yield stress (= shear stress, just before stopping of motion)
BYS = Bingham yield stress (= yields stress in the two-parameter Bingham visco-plastic model)

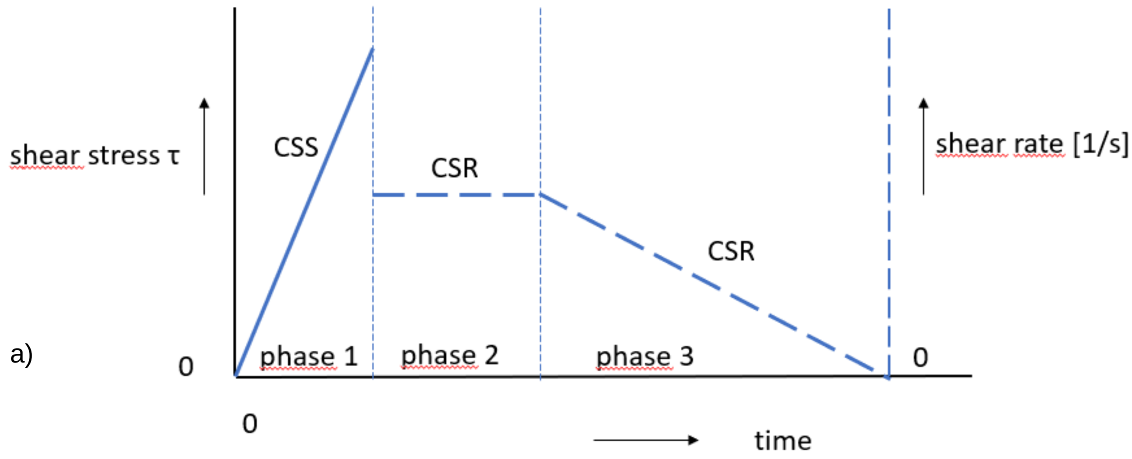
The DYS is the lowest of these three, and SYS is the highest.

For deposition, i.e. in order that the just sprayed material remains in place, the DYS seems relevant at first glance. Without considering dewatering the material will grow strength, leading i.e. to SYS. Before the next round of spraying, sufficient dewatering in combination with strength gain, needs to have taken place the bear the next layer. In fluid flow characterisation the BYS can be used but may be too high at low shear rates.

For fluid flow also the shear stresses under flowing conditions need to be characterized. The flow remolds the material. Simplest approximation is to quantify by yield stress and plastic viscosity of the Bingham model.

Protocol
A measurement protocol needs to applied to enable finding the relevant parameters. The strength of the unremolded material needs to be characterized, and yield stress and viscous properties of the remolded conditions need to be found.

A protocol consisting of 3 phases is applied, see figure below:
-in the first phase the shear stress increasing linearly with time (this is called “controlled shear stress” mode: CSS). This aims to find SYS.
-in the second phase a constant shear rate is applied (a “controlled shear rate” mode: CSR), this is to remold the material (after failure in phase 1, the rotoviscometer will commence rotating fast, but is limited to a value twice the constant shear rate of phase 2).
-in the third phase the shear rate is linearly decreased to zero (also a CSR). This gives the remolded properties: DYS, and upon fitting the BYS and plastic viscosity.



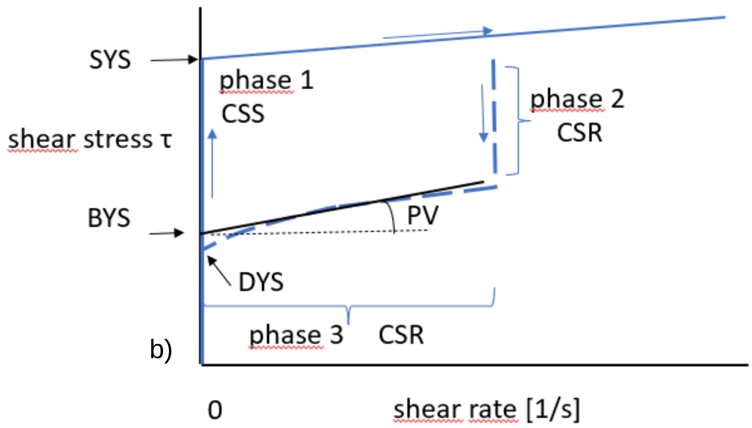


Figure 10.2: Sketch of measuring protocol: a) time-sequence, b) associated measured flow curve.

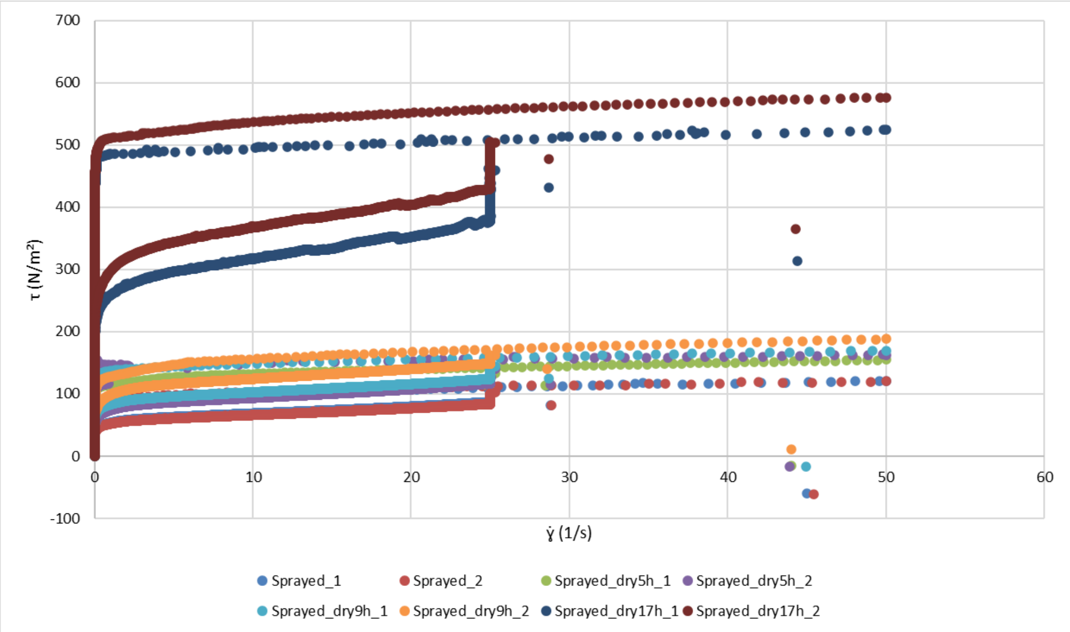


Figure 10.3: All rheological measurements: Shear stress as a function of shear rate.

C.3.2 Yield stress

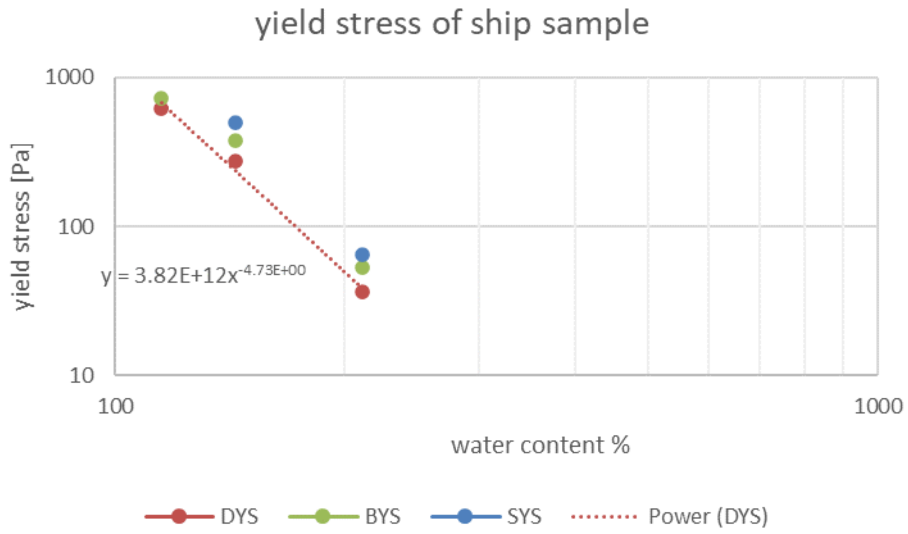


Figure 10.4:Samples from ship (143 % water content), dredged from the saline Waddensea side of the Harbor of Lauwersoog, left for 5 h WC115% (SYS out of range rheometer protocol >600 Pa), and diluted with seawater WC=211 %. The latter is the same as sprayed (batches without freshwater dilution).

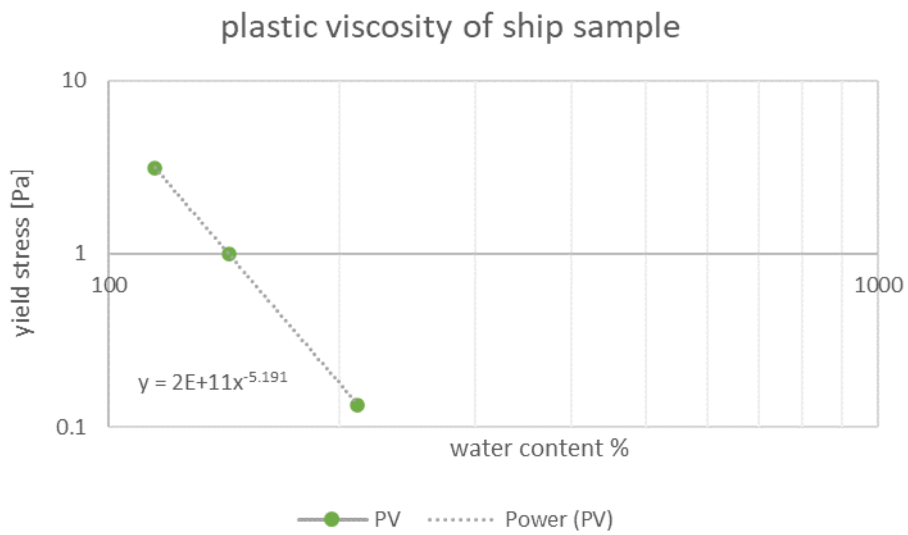


Figure 10.4:Plastic viscosity of Bingham model (remolded conditions).

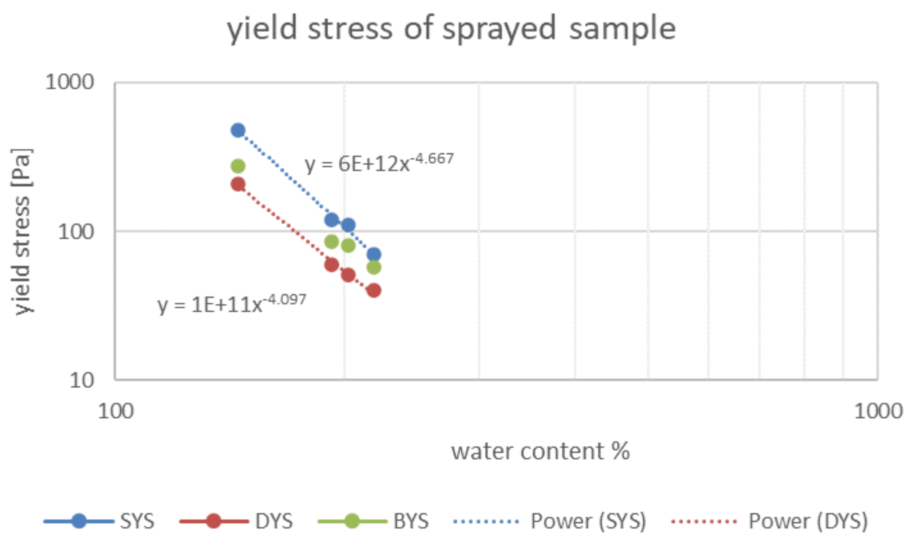


Figure 10.5: Yield stresses, as a function of water content (sample diluted with fresh water before loading in traveling slurry tank).

Rheological measurement, Figure 10.5, shows that strength increases with decreasing water content to the power 4. So, a little bit of variation in water content has a large effect on strength, hence influences the thickness of the layer that will remain stable on the dike.

C.3.3 Plastic viscosity

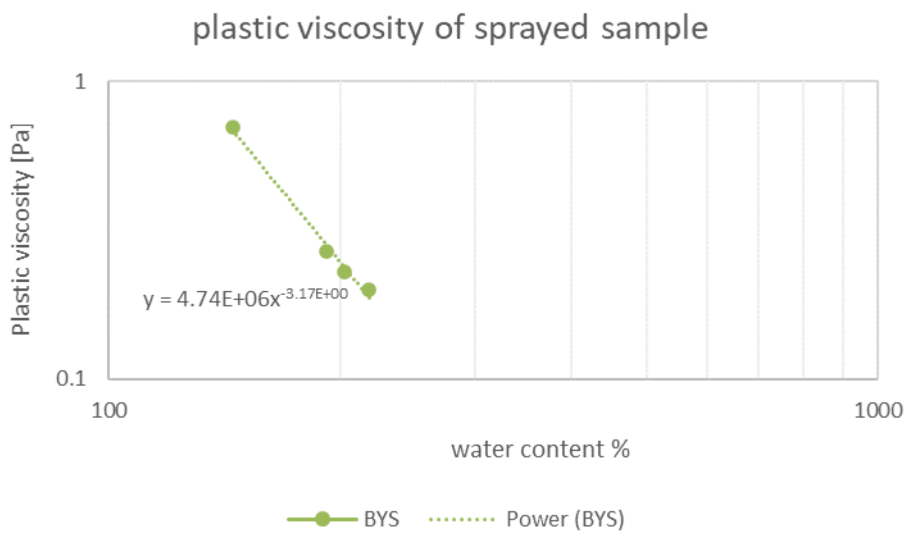


Figure 10.6: Plastic viscosity as a function of water content

C.3.4 Fitting by power law rheological model

On some occasions it is necessary, despite yield stress, to fit the flow curve by a power law model. This may be the case when there is only power-law based fluid flow theory available (because in mathematics the power-law integrates and differentiates nicely). In that case Bingham type of behavior can be approached by a low value for the power-exponent. See Figure below for curve fitting of the remolded flow curve by power law.

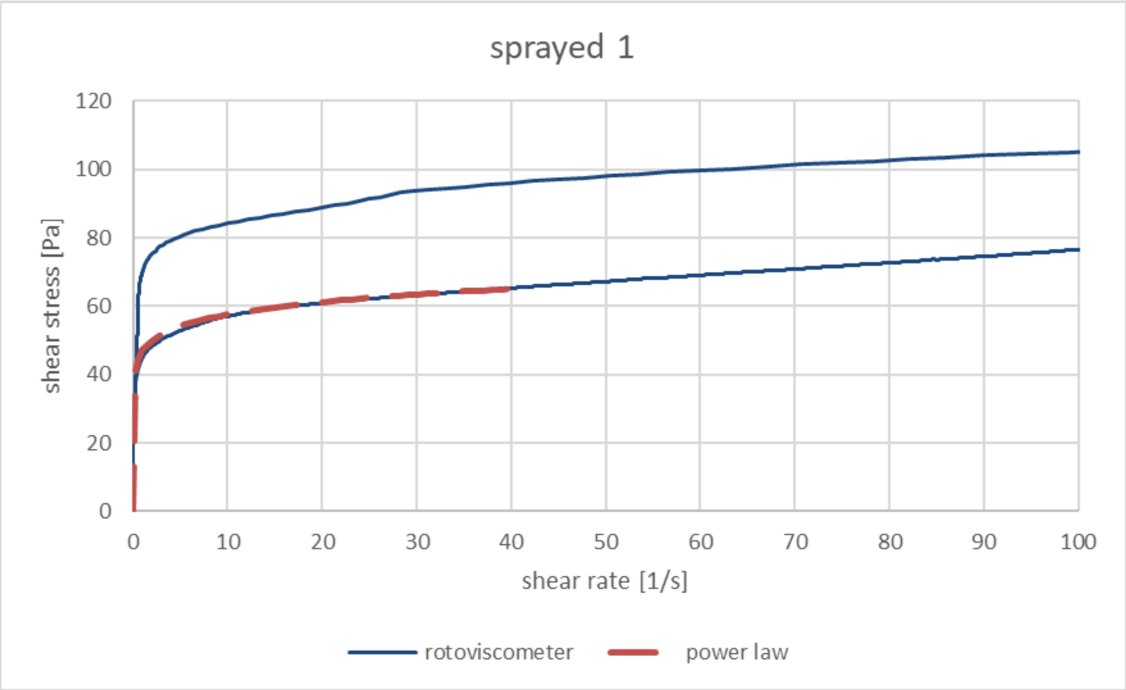


Figure10.7: Curve fitting remoulded flow curve by power law: $\tau = 47\left(shear \quad rate\right)^{0.088}$

C.3.5 Influence of type of water dilutant

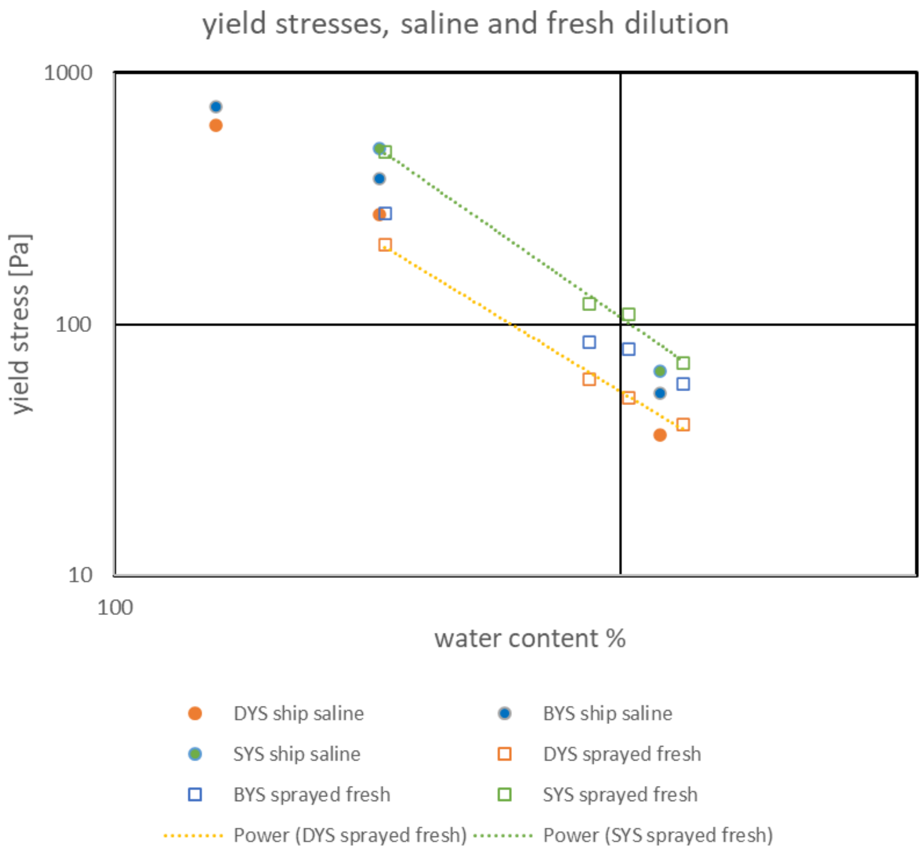


Figure 10.8: Comparison of samples diluted with fresh and saline water.