TKI Living Lab for Mud

Research, dissemination, upscaling

EcoShape

Colofon

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The EcoShape TKI-LLM project was mainly carried out by EcoShape partners Deltares, HKV, Van Oord, Boskalis and Wetlands International. In addition to these partners, other EcoShape and non-EcoShape partners participated actively in activities correlated to this project: Hogeschool van Arnhem en Nijmegen, Provincie Groningen, NETICS, Wageningen Marine and Research, Witteveen en Bos, Royal Haskoning DHV, Hogeschool Van Hall Larestein and te Technical University of Delft. This activity has been co-financed via the PPS-innovation program subsidy of the Ministry of Economic Affairs & Climate.

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Summary

Building with mud (e.g. fine dredged sediment) is an important innovation area for the Netherlands with significant potential applications in the Netherlands itself and internationally. This importance is underlined by the recent realization of sand being a scares resource and by the development of circularity principles.

Building with Mud addresses two global challenges:

1. The sediment balance of delta systems with areas of too high sediment concentration and siltation in ports and areas of coastal retreat or land subsidence; and
2. The shortage of building material in these deltas, especially where sand is scarce or where building material needs to come from far.

With optimum sediment management these two challenges can be connected, with beneficially relocation from sediment in excess to starving areas or use in other beneficial applications. Typical Dutch examples of beneficial use applications include feeding or building salt marshes in front of a dike, building natural islands, using ripened dredge sediment as clay for dikes and raising or improving agricultural land.

These applications largely leverage on nature-based solutions, in fact, sediment is the foundation of effectively all nature-based solutions in water environments. These solutions improve the functioning and the quality of water systems. They protect against flooding and they improve the productivity of agricultural land. Building with Mud is therefore central to various objectives of the Knowledge and Innovation Agenda.

In the Netherlands alone, there are various initiatives that try to develop knowledge on Building with Mud at local or regional level, such as the Eems-Dollard 2050 program, the Marker Wadden or the Program Large Waters. EcoShape plays a prominent role in these programs. Within and beyond these programs, EcoShape runs, is or has been significantly involved in various pilots that focus on sub-aspects of Building with Mud. To ensure that the knowledge generated in these projects can be applied generically in new products, technologies and market projects, it is necessary that the ongoing research is appropriately connected between problem holders and experts in a broad national and international network.

In 2016 EcoShape introduced the Living Lab for Mud initiative to start connecting the knowledge on BwM developed in its pilots with the practitioners and external community. The Living Lab for Mud was represented in an illustrative folder and presented at various events.

At the end of 2018 this Toegepaste Kennis Innovatie (TKI) Living Lab for Mud project was initiated with the main objectives of:

- Conducting new interconnecting research with explicit focus on bridging, integrating and leveraging upon the data, experience and results of the ongoing pilots of the EcoShape Living Lab for Mud initiative;
- Translate this knowledge into practical guidelines and lesson learned;
- Disseminate this knowledge within and beyond the EcoShape community with proactive participation and leadership in relevant (inter)national professional networks; and
- Use this knowledge to create spin-off for other research and market projects as well as upscaling programs focussed on mainstreaming Building with Mu and nature-based solutions at landscape scale.

In line with these objectives, this project supported three main activities:

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1. New interconnecting research, ~80%;
2. Dissemination and leadership of (inter)national initiatives, ~10%;
3. Knowledge spin-off and upscaling, ~10%.

The new interconnecting research focused on processes to optimize the transformation of dredge soft sediment in soil or clay, with specific attention for ripening and desalinization of salty sediments. It also initiated the monitoring of potential greenhouse gas emission from ripening dredge sediments in relation to natural systems. These topics are indeed important current research topics in the Netherlands and with high potential export abroad.

Dissemination and leadership involved participating in networks internal and external to EcoShape, national and international. In addition to various publications, EcoShape played an active role chairing CEDA and PIANC working groups on Beneficial Sediment Use. It participated to various national and international events, often with prominent or keynote roles. EcoShape and Dutch experience on this topic was also utilized and references in international publications, such as the US Corps of Engineer Atlases. Finally, since 2021 EcoShape started a Beneficial Sediment Use table as a key activity within the new EcoShape structure.

This project supported the connection and the start-up of other related initiatives. It contributed to Phase 1 of the Meegroeidijk, which is an innovative technology (based on old practices) to apply dredge sediment in thin layers on existing dikes. This allows for slower but continue dike improvement and strengthening, implementing locally available material. It also linked to the NWO Project Hedwige-Prospetpolder to study how management realignment can be used as a NbS for flood safety. Specifically, this project investigates the mutual contribution of vegetation and soil strength development in front of realigned dikes to reduction of risks in case of dike breach. Finally, this TKI Living Lab for Mud project allows to connect this knowledge to ongoing market projects, especially in the Eems-Dollard region and in particular to the Pilot Raising Agricultural Land and to the VLOED Program, which explicitly investigate the technical as well as socio-economic scalability of using dredge sediment to build dikes and raising agricultural land at regional scale.

This TKI Living Lab for Mu project provides a variety of results, from innovative applied research to dissemination and spin-off. This report gives a comprehensive and general overview of the main results, highlighting the link between projects and translation of knowledge in practical lesson learned, dissemination and upscaling. The detailed results of each research task are included in the appendixes, each of them being an independent report. As much as possible this report refers to the relevant references and links to the various dissemination initiatives. Beyond this report, this project leaves a network of experts and a community connected around the Building with Mud topic, which will be instrumental to assure uptake of these solutions in the market and policies.

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1 Introduction

Building with mud (BwM, e.g. fine dredged sediment) is an important innovation area for the Netherlands with significant potential applications in the Netherlands itself and internationally. BwM addresses two global challenges:

1. The sediment balance of delta systems with areas of too high sediment concentration and siltation in ports and areas of coastal retreat or land subsidence; and
2. The shortage of building material in these deltas, especially where sand is scarce or where building material needs to come from far.

With optimum sediment management these two challenges can be connected, with beneficially relocation from sediment in excess to starving areas or use in other beneficial applications. The importance of BwM increases with the recent realization that sand is becoming scarce (Vörösmarty et al., 2003) while billions of cubic meters of fine cohesive sediments are dredged worldwide to maintain navigation channels. Consequently, more and more of these fines will have to be used in infrastructure development (Barciela-Rial et al., 2020).

Further, beneficial sediment use is also in line with circular economy to achieve sustainability goals, which is a worldwide trend among policymakers. In this line, the Netherlands has committed to be completely “circular” by 2050 (Rijksoverheid 2017). Simultaneously, around 1900 km of the Dutch dikes must be reinforced before 2050 to comply with new safety requirements. This implies the need to develop re-use scenarios and sustainable sediment sources for infrastructure projects and industry (Besseling et al., 2019, 2021a and 2021b, Haarman, 2020).

Typical Dutch examples of beneficial use applications include feeding or building salt marshes in front of a dike, building natural islands, using ripened dredge sediment as clay for dikes and raising or improving agricultural land. These applications largely leverage on nature-based solutions (NbS), in fact, sediment is the foundation of effectively all NbS in water environments. These solutions improve the functioning and the quality of water systems. They protect against flooding and they improve the productivity of agricultural land. BwM is therefore central to various objectives of the Knowledge and Innovation Agenda (KIA).

In the Netherlands alone, there are various initiatives that try to develop knowledge on BwM at local or regional level, such as the Eems-Dollard 2050 program, the Marker Wadden or the Program Large Waters (PAGW). EcoShape plays a prominent role in these programs. Within and beyond these programs, EcoShape runs, is or has been significantly involved in various pilots that focus on sub-aspects of BwM. To ensure that the knowledge generated in these projects can be applied generically in new products, technologies and market projects, it is necessary that the ongoing research is appropriately connected between problem holders and experts in a broad national and international network.

In 2016 EcoShape introduced the Living Lab for Mud (LLM) initiative to start connecting the knowledge on BwM developed in its pilots with the practitioners and external community. The LLM was first presented at CEDA (van Eekelen et al., 2017) and pitched as a possible pilot initiative under the International Water Ambition (IWA). In 2017, EcoShape received a small grant from the IWA to develop an illustrated vision for LLM (EcoShape, 2017). During the same year, EcoShape proactively pitched the LLM concept with a number of presentations and papers in the Netherlands and internationally (Sittoni et al., 2019a and 2019b).

At the end of 2018 this TKI Living Lab for Mud project (TKI-LLM) was initiated with the main objectives of:

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- Conducting new interconnecting research with explicit focus on bridging, integrating and leveraging upon the data, experience and results of the ongoing pilots of the EcoShape LLM initiative;
- Translate this knowledge into practical guidelines and lesson learned;
- Disseminate this knowledge within and beyond the EcoShape community with proactive participation and leadership in relevant (inter)national professional networks; and
- Use this knowledge to create spin-off for other research and market projects as well as upscaling programs focussed on mainstreaming BwM and NbS solutions at landscape scale.

In line with these objectives, this project supported three main activities:

1. New interconnecting research, ~80%;
2. Dissemination and leadership of (inter)national initiatives, ~10%;
3. Knowledge spin-off and upscaling, ~10%.

This TKI-LLM project significantly leverages on the ongoing pilots and initiatives, without which it would not have been possible. All the additional research activities make especially use of material, site-access, data, modeling tools and field experience of the Kleirijperij (Clay Ripening) en KIMA Marker Wadden pilots. This critical information is made available as in-kind contribution to this TKI-LLM project.

This report gives a comprehensive and general overview of the main results, highlighting the link between projects and translation of knowledge in practical lesson learned, dissemination and upscaling. The detailed results of each research task are included in the appendixes, each of them being an independent report. Specifically, Section 2 of this report describes the main results of new interconnecting research. Section 3 describes the dissemination and leadership activities and Section 4 the knowledge spin-off and upscaling.

2 New interconnecting research

This research focussed on deepening the processes that play a critical role in turning dredge fine sediments into soil in Dutch fresh and salty water environment: ripening and desalination. This research also leverages on the availability of a fresh dredged sediment deposit (i.e. Clay Ripening Kwelder) to measure greenhouse gas (GHG) emission from salty dredge sediments exposed to the atmosphere.

The need for new complementary research and the translation to practical guidelines on the topics ripening, dissemination and GHG emission from ripening sediments was especially highlighted by the ongoing pilot projects Clay Ripening and the KIMA Marker Wadden. Both pilots test how to turn fine dredge sediments into soil: clay for dike construction the former and substrate for natural island the latter. Both projects carry out independent research on ripening of fines dredge sediments, salty for the Clay Ripening, fresh for the Marker Wadden. This TKI-LLM project provides a unique opportunity to develop new knowledge merging, comparing and integrating the data and the results of these projects to come up with a set of common theoretical principles, computing tools and practical lesson learned.

The pilot Clay Ripening indicated salt as a high-risk parameter for the successful application of ripened locally available salty dredge sediment as clay for dikes or as soil to raise agricultural land. After three years of ripening, the salt content of the clay was still relatively high. The pilot highlighted therefore the importance to evaluate alternatives to reduce the salt content of the dredge sediment before it is deposited in the dewatering basins. In 2020 the pilot POL (Raising Agricultural Land) was initiated to test the feasibility of using dredge sediment to raise sinking agricultural land. This pilot tests the effect of rinsing the dredge material after dredging and before pumping it to its final destination. Leveraging on the experience of the Clay Ripening and on the availability of POL, Hogeschool van Arnhem en Nijmegen (HAN), the Province of Groningen, NETICS and EcoShape joined forces to initiate a parallel research project to evaluate how to best decrease the salt content of dredge sediments. This project was supported by different sources including the KIEM subsidy and this TKI-LLM project.

Understanding the contribution to GHG emissions of ripening dredge sediment deposits is a topic of current interest as a potential contributor to the global carbon emission balance. While it is well known that natural systems are great contributors to the carbon balance, as far as emissions but also sequestrations, the specific contribution of dredging or earth moving activities beyond that of machineries is less known. The availability of ripening deposits of the pilot Clay Ripening offered an opportunity to measure GHG emissions. In addition to field data and their interpretation, this task produced a literature review that collects current state-of-the-art knowledge to build upon. This task is to be seen a starting point to gain experience with measuring GHG from salty dredge sediment exposed to air in the field. This is a specific application in a specific location, which should not be extrapolated generally. It is therefore important to frame this research and its results in the broader picture to contextualize the message appropriately. Characterization of emission and sequestration potential of natural systems and of earthmoving (soil and sediment) activities in the broader sense is currently an ongoing initiative of the EcoShape Beneficial Use of Sediment table (see Section 2).

2.1 Ripening of dredged sediment

This section describes the main findings of the new complementary research regarding ripening. This research project developed a common state-of-the-art base of knowledge and practical experience on consolidation and ripening of dredged sediment. This research combines expertise of physical processes with numerical modelling and experience from large-scale pilots. The large-scale pilots which are considered in this scope are the Marker Wadden pilot experiments (KIMA) and the Clay Ripening pilot.

The project was jointly carried out by experts from Deltares, van Oord, Boskalis and HKV, combining research, engineering and implementation expertise. Deltares coordinated the project.

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The project is divided into two main parts: a knowledge development part and a practical application part. This section of this report provides a summary of the most important findings from the different project phases. A detailed description of the project results is reported in Appendix A

2.1.1 Ripening processes and model

The knowledge development part included:

- A literature review to define the state-of-the-art knowledge on ripening;
- The development of a conceptual model to highlight the most important physical processes regarding ripening;
- Applying an existing numerical model for both Clay Ripening and KIMA to study different ripening scenarios;
- The development of a new and improved numerical tool (Deltares 1DV) to capture missing but significant processes, designed to allow further expansion to other processes (e.g. biochemistry or GHG) in the future.

2.1.1.1 Literature review

Ripening of mud involves physical, chemical and biological processes. Which of these processes are relevant depends on what the mud is ripened for, as the required properties may differ per application. For instance, if the geochemical state and amount of organic matter contained within the muddy deposit are relevant, chemical and biological processes must be carefully considered. For the dewatering of muddy deposits and thus strength development, physical ripening is dominant (Van der Meulen, 2012; after Pons and van der Molen, 1973). In the considered pilots, dewatering of the deposits was a key process. Therefore, this subproject mainly focuses on physical ripening. In the remainder of this chapter, if ripening is mentioned, this means physical ripening.

From an engineering point of view, physical ripening is a process in which the mechanical behaviour of a given mud with a certain quality is improved (transformed) to a level that can be used in an application of interest. Hence, the criteria to judge if a soil is ripened or not depend on the specific application and design requirements, which may differ per project.

For most large-scale engineering applications, a mud deposit undergoes three main phases during the ripening process (Figure 1): (hindered) settling; self-weight consolidation; and desiccation. During all three phases, there is a water flux from within the mud deposit to outside, eventually resulting in a denser deposit. However, the driving force behind this water flux differs. For settling the driving force is gravity, while for self-weight consolidation it is a combination of gravity and excess pore pressure gradients. For desiccation, it is surface evaporation. The settling phase generally lasts for hours to few days, while consolidation and desiccation may take months or years, strongly dependent on layer thickness, drainage and climate conditions. The terms “ripening” and “desiccation” are not exchangeable. Ripening includes the entire transformation process from fresh mud to soil, including the non-physical processes. Desiccation (i.e. drying) specifically refers to removal of water from a deposit under the influence of evaporation.

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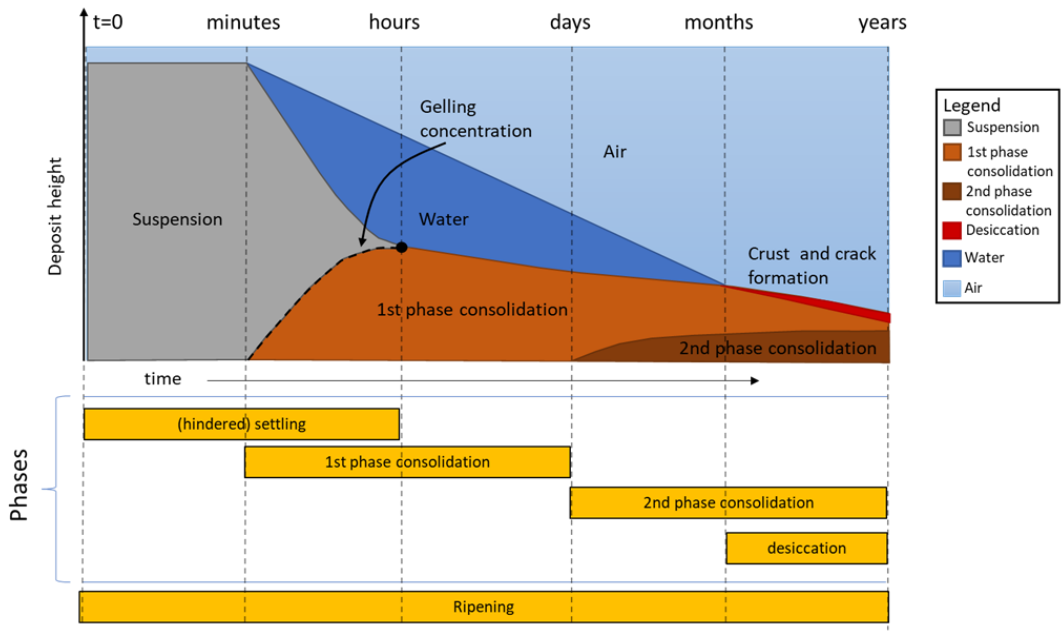

Figure 1. Schematic representation of the (physical) ripening process, indicating the different phases and their chronology. Associated timescales for the different phases are also indicated. Adapted from Talmon et al. (2019).

2.1.1.2 Conceptual model

A conceptual model was developed which includes all phases in the ripening process. For each phase, the driving force and key parameters are listed in Figure 2. By using the concept of lumped modelling, we can link the key parameters to combined effects for each phase. In such a lumped modelling approach, the effect, interaction and interdependence of microscopic details are summarized into one or a few overarching parameters or functions. These are called (lumped) material parameters or (lumped) material functions. This approach provides a way to derive good estimates for each of the three phases. Though these do not capture the full complexity and temporal evolution of a ripening deposit, they can prove very useful as a first estimate.

The settling phase is mainly described by the (hindered) settling velocity. Whether the settling phase occurs depends on the initial concentration of the suspension and whether this is smaller or larger than the gelling concentration. If it is smaller, settling takes place and segregation of particles within the deposit is likely to occur. Consolidation is categorized into first phase (governed by permeability) and second phase (governed by effective stress development) consolidation (Figure 2). The time scale of first phase consolidation is in the order of a few days to a week. The time scale of the second phase of consolidation is in the order of several months to years during which gradually the water will be expelled from the deposit.

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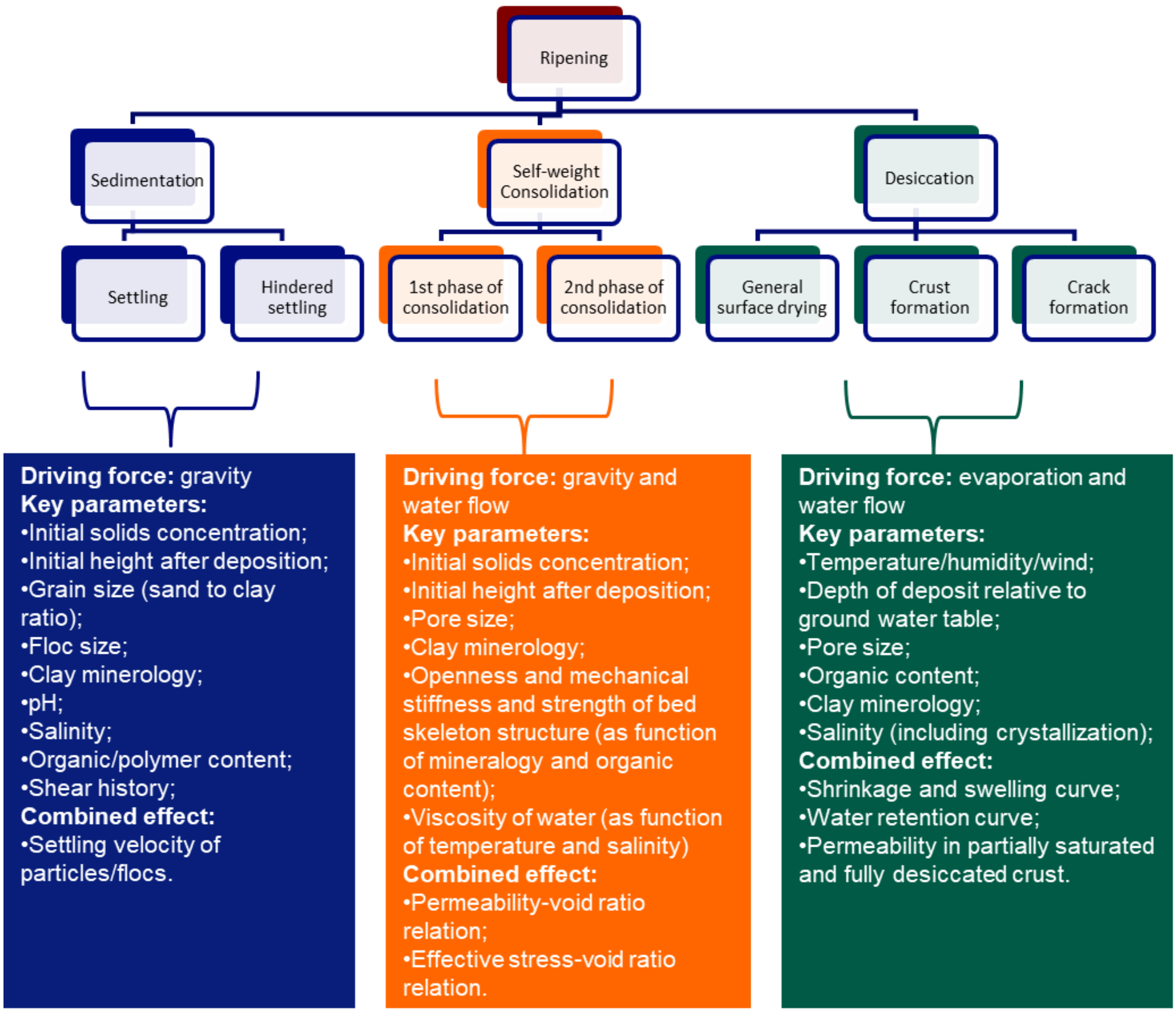

Figure 2. Summary of governing processes during ripening process, and their combined effect.

The two main features of desiccation are cracks and crust formation (Figure 2. Summary of governing processes during ripening process, and their combined effect.Figure 2). Cracks promote dewatering by exposing a larger surface area to the atmosphere. The depth of crack is limited mostly up to the ground water table. Crust formation hampers dewatering by reducing capillarity and permeability of crusted layer. The depth of the crust is mostly limited by the depth of the cracks. The formation of the crust introduces surcharge on the non-crusted deposit below the crusted layer. This may evoke further consolidation of the deeper layers in the deposit. The water flux induced by this effect is most likely expelled from the side cracks.

At the onset of the desiccation phase (just after surface water runoff) the evaporation flux is completely governed by weather conditions. Heat in combination with low humidity encourages crack formation, while organic content and potential salt (in case of salty dredge sediments) mitigate crack formation and development. As the soil moisture decreases, transport within the soil becomes a limiting factor and both evaporation and internal transport govern the water flux out of the soil. In the end, when the moisture content of the soil surface becomes very low, the water flux is completely governed by internal transport.

To a certain extent, cracks provide drainage and the exposure of moist soil to air, but this process may be enhanced, e.g. by factors as:

- Bottom drainage and ditches to enhance dewatering;
- Reworking/ploughing by exposing wet soil to atmosphere;
- Making heaps to increase the soil surface area; and vegetation.

2.1.1.3 Hindcast modelling of the Clay Ripening and KIMA pilots

The existing Vardon model, fine-tuned for ripening of Dutch sediments during the Clay Ripening pilot, was applied to evaluate a broader range of ripening strategies and the effect of non-uniform properties in the deposit. These evaluations were beyond the original scope of the pilots themselves. Lesson learned during these pilots suggested these to be potentially significant additional information to be evaluated. The same numerical model was applied to the Clay Ripening and the KIMA pilots leveraging on the data provided by these pilots themselves.

For the hindcast modelling, the ripening model which was developed by Vardon et al. (2014) was applied. The model computes the water content ratio for each cell in the model domain, based on given shrinkage, water retention and permeability curves. Water is conserved, it either evaporates or flows down/up. Water flows from high to low potential (analogy: flow from high to low pressure).

This model allows for flow behavior in saturated and partially saturated conditions, bottom drainage, specified or computed net evaporation-precipitation, and effect cracks on permeability, though the crack depth is fixed. Some key limitations include the lack of the settling phase, of the effect of successive drying and wetting cycles on soil properties such as shrinkage curve and water retention curve, and different soil properties that cannot be modelled. This model is thus only suitable for stacked layers of deposits with similar material properties.

Application to the Clay Ripening

The Vardon ripening model was calibrated and validated during the Clay Ripening pilot. This project built upon these results and extended these with hindcast modelling and scenario analysis. In general, simulation results are in good agreement with the Clay Ripening pilot field data for the first year, regarding both settlement and density profiles.

At later stages, the agreement between the model and measured crust density is sometimes less. Three factors may explain this: (1) the assumed effect of a dry crust on permeability (e.g. crack formation), (2) reworking of the deposit (inclusion of air pockets, 2D/3D effects in mounts) or (3) changing material properties due to alternating drying-wetting in the crust.

In the scenario analysis, the effect of three design factors were studies: bottom drainage, initial deposit height and climate. The initial deposit height was found to be the most important factor steering the time scale of the physical ripening process. An initial deposit height between 40 to 60 cm seems to be optimal for rapid consolidation and desiccation. The difference between dry and wet years is substantial. In three subsequent wet years ripening proceeds less than in two subsequent dry years. In case of a higher initial deposit height, the presence of drainage can speed up the ripening process by several months (3 months in 3 years).

Application to KIMA

The Vardon ripening model was successfully calibrated and validated for the KIMA pilot experiments. Application of this model was not in the scope of the pilot. This hindcast modelling exercise focused on the heterogeneity in material properties over different compartments. This heterogeneity is due to the source material, the filling process itself and the size of the compartments. The simulation focused on two distinct compartments: the first one nearby the filling location, the second one at the far end of the compartments.

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In general, simulation results are in good agreement with field data for the first year, regarding both settlement and density profiles. The initial density at the nearby location was high, since the filling process took more than a month. Settlement was relatively limited, and a crust developed during the pilot. At the far end of the compartments, initial density was rather low and thus settlement was high. These initial conditions dominate over differences in material properties. For the far end of the compartments, the large settlement also meant that the deposit was submerged for most of the pilot period. Hence, crust formation did not take place here.

The calibrated model is suitable for scenario analysis, which could be carried out as a follow-up activity.

2.1.1.4 Development of Deltares 1DV ripening model

A series of different models exist that evaluate different aspects of the transition from (dredge) sediments to soil. The Vardon model is a good example, which is specifically developed for computing thin layers deposition, offering a good tool for ripening estimates. Other models include a more accurate prediction of the consolidation phase and can include other processes, like biogas generation from sediments, like Delcon (van Kessel, 1999) or FS-Congas (Wichman, 1999). Processes such as ripening and biogas generation demand more and more for the development of consolidation models that include a biogeochemical component. Further, all these different models may benefit from a single comprehensive tool.

In line with these needs and partially sponsored by this TKI-LLM project, Deltares initiated the development of a 1DV consolidation model that will capture these processes. The 1DV consolidation model is based on the existing 1DV model, which is computationally consistent with Delft3D. During the LLM-TKI model the focus went to the development and testing of the consolidation and desiccation processes. The plan is to continue this development including the biogeochemical processes during the NWO Sediment to Soil project. This is a research project lead by the Technical University of Delft with EcoShape and various EcoShape partners involved. The project starts in 2022 and will continue for four years.

The 1DV consolidation model is based on the work of Merckelbach and Kranenburg (2004) and was used as a starting point for this phase. This model includes both (hindered) settling and consolidation. To make it suitable for the entire ripening process, desiccation was included. This task was carried out aligning the scope of this project with the internal strategic research activities of Deltares.

The 1DV ripening model covers the main governing physical processes a fresh mud may undergo during the ripening process. In comparison with the Vardon model, it specifically includes the settling phase, stacking layers with different soil properties, different types of bottom drainage i.e. sink, natural drainage etc., accurate physical descriptions of the involved processes, e.g. by considering both the air pressure and saturation degree in the main equations. Because the model is still currently under development, a definitive report is not available. However, a status update presentation is attached to Appendix A.

2.1.2 Practical guidelines for optimal ripening

Practical guidelines for BwM projects were written together with all project partners, leveraging on and integrating the lesson learned from the developed knowledge and on the practical experience in the field acquired during the pilots Clay Ripening and KIMA. These practical guidelines are oriented towards application of this experience in practical market projects, in the Netherlands and abroad. Since physical ripening is dominant over the other involved processes, this guideline focusses on physical ripening and how it can be controlled.

As we mentioned before, physical ripening is a process in which the mechanical behaviour of a given mud with a certain quality is improved (transformed) to a level that can be used in an application of interest. The application of interest has a central role. It prescribes the characteristics of the final product and the trajectory, means and tools to achieve this goal. The choice for any of these means and tools depends on initial mud quality, budget, time, climate, space, and design philosophy (Figure 3).

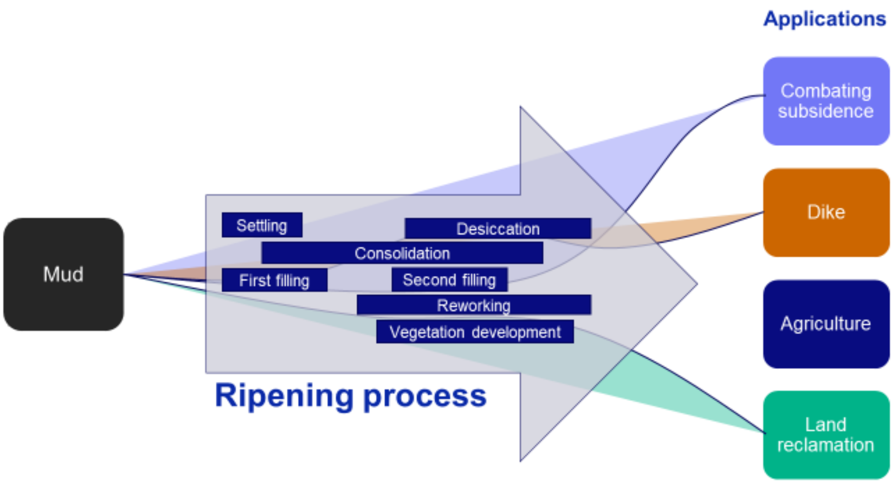

Figure 3. This figure conceptually shows the ripening process. In this process, the properties of a given soil / mud (on the left) are transformed (middle arrow) to a level that it can be used in an application of interest (on the right). Within this process, several means and tools can be used to achieve the goal. Possible actions include filling a deposit using multiple layers or reworking the material or promoting vegetation development. The choice for any of these means and tools depends on initial mud quality, budget, time, climate, space, and philosophy.

Many control measures exist when it comes to the ripening process. These include both project design and execution phases. These are described in detail in the guideline in Appendix A. The main conclusions from these guidelines are:

- Most importantly, the best strategy for a fill depends on the final requirements:
  - Requirements and climate conditions determine the ripening strategy. This includes when and how to start the ripening process.
  - For wetland creation, the required strength of the surface layer is relatively small. In this case, the main challenge is to efficiently use the building material. The best strategy would then be to construct the fill using multiple low-density layers, letting thin crusts form on each layer. In this case, most of the vertical profile is not dry, so not overconsolidated. This results in efficient material use, i.e., a large volume while using only a limited amount of solids. If most of the profile is overconsolidated, too much sediment is used for this specific purpose.
  - If the fill is used for construction purposes, this requires stricter strength and settlement conditions. Hence, overconsolidation is necessary. Intermediate steps of drying the material are possibly required before transporting material to the final fill (e.g. first ripening the material first, then rehandling it as a reclamation fill). To make this cost efficient, ripening and reclamation sites should be nearby or even at the same location.
- Key recommendations:
  - The desired application or final result (e.g. clay for dikes or natural islands) determines the entire ripening process and engineering / operational activities.
  - Layer thickness and water table level are two of the most important parameters:
    - Layer thickness influences dewatering and thus ripening time quadratically.
    - Water table level determines desiccation or not, thus if the deposit develops a crust, influencing the ripening process. Also, presence of water influences the development of vegetation (type).
  - Minimize reworking as much as possible. Let the atmosphere or nature do the work. The most effective reworking to accelerate ripening appears to be the removal of the crust to expose fresh sediment to the atmosphere.
  - Transport is expensive and troublesome, especially by road. Ripening and application sites should be nearby, preferably at the same location. Also, maximizing connection between supply and demand is critical.

2.2 Desalinating dredged sediment

This task of the TKI-LLM project was coupled to the larger "Desalination of Dredged Sediment for Delta Protection project". In this larger project, the research group Sustainable River Management of the HAN, EcoShape, NETICS, in collaboration with parties united in the intergovernmental project IBP-VLOED, investigated how marine dredged sediment can be (cost) effectively desalinated, so that the impact of salt is decreased on agricultural field or dike clay. The TKI-LLM contributed to the project offering expert supervision to HAN students and lab support. In return, the results of the larger project are made available to TKI by the consortium.

The behavior of dredged sediment varies largely as a function of the composition of its solid fraction (e.g. Barciela-Rial et al. 2020, 2022). Furthermore, given the cohesive properties of fine dredged sediment, salts have a flocculant effect on cohesive sediment. Therefore, the decision of what is the most suitable desalination method is not straightforward. This "Desalination of Dredged Sediment for Delta Protection" project investigated the effect of mixing with fresh water for desalination. This was done by studying different small-scale mixing techniques and mixing times in order to mimic potential in situ suitable cost-effective desalination methods (strategies) at a bigger scale (Barciela-Rial et al., 2021). Specifically, this task of the TKI-LLM quantified the effect of the mixing with fresh water on the concentration of dissolved ions (salt and nutrients) and the changes in concentration with time.

2.2.1 Method and hypothesis

The first step to design a cost-effective desalination strategy is to understand and quantify the salt gradients in a consolidating water-sediment mixture. Settling experiments after mixing sediment dredged at the proximity of the Ems Harbor with fresh water were performed to understand this gradient and study its evolution over time. The sediment used is the same as in the Pilot Ophoging Landbouwgronden[1] (POL) project. This pilot is part of the Eems-Dollard 2050 program and aims at investigating the feasibility of turning fresh salt dredge sediment into agricultural soil. In POL, sediment is dredged in the port of Eemshaven and rinsed with fresh water before it is deposited on an agricultural parcel where it is let ripen into agricultural soil.

The hypothesis was that during the settling and consolidation experiment a different gradient of ion concentration occurs, being the salt concentration smaller at the upper end of the column and higher in the pores of the consolidating sediment. To study if such stratification on the concentrations occurred, samples were taken at different layers of the supernatant material. A total of 62 extra samples were taken for detailed Dionex ion chromatography and thermogravimetric analysis TGA, to determine organic matter present in the sediment. Figure 4 shows the sampling procedure.

[1] https://eemsdollard2050.nl/project/ophogen-landbouwgrond-programma-eems-dollard-2050/

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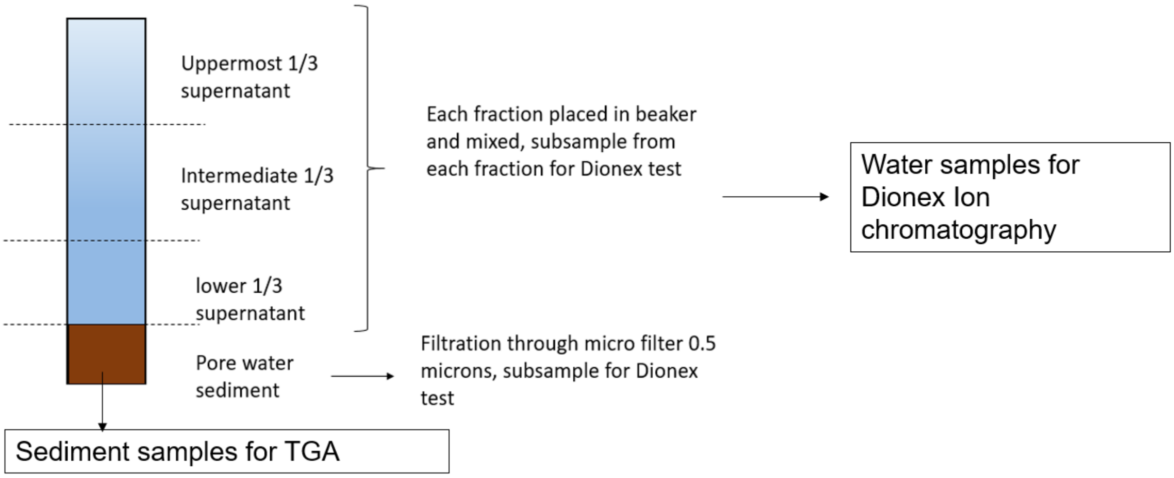

Figure 4. Sampling method

The dredged sediment was mixed with fresh water from the tap at a (volume) ratio 1:6 with a HOBART planet N-50 Mixer. The mixing time was 5 minutes at a constant mixing rate of 285 rpm/minute (corresponding to the intermediate speed of the device). 285 rpm/minute was high enough to completely mix the sediment - water mixture but not too high to create splashing of the sample or destroy the microstructure. The water content of the resulting slurry was determined in the oven by oven drying at 105 degrees, 24 h.

After mixing with fresh water, the resulting mixture was directly poured in 250 ml glass columns for the performance of settling/consolidation experiments (see *Figure 5*) and periodic sampling according to the procedure shown in Figure 4. The 250 ml glass columns were provided with: 1) volume marks and 2) measuring tape with metric units in order to quantify the settling. The experiment started with 18 columns where the mixtures were allowed to settle and consolidate (*Figure 5*). The settling of the sediment-water interface was monitored. Samples were taken from 3 replicates at each of the following times: t = 1 day, t = 3 days, t = 7 days. In order to check the effect of a second mixing cycle, for 9 of the 18 column replicates, the sediment that was consolidating in the columns was remixed again at t= 7 days. The mixing was done with the supernatant water of the column (i.e. not with tap water) and with the same mixing procedure (5 minutes at 285 rpm/minute). For these columns, samples were also taken from 3 replicates at t = 8, 10 and 14 days. At all sampling times, the total mass of the column and the mass of the different fractions (mass of supernatant and mass sediment bed) was measured. The EC of the supernatant water was also measured

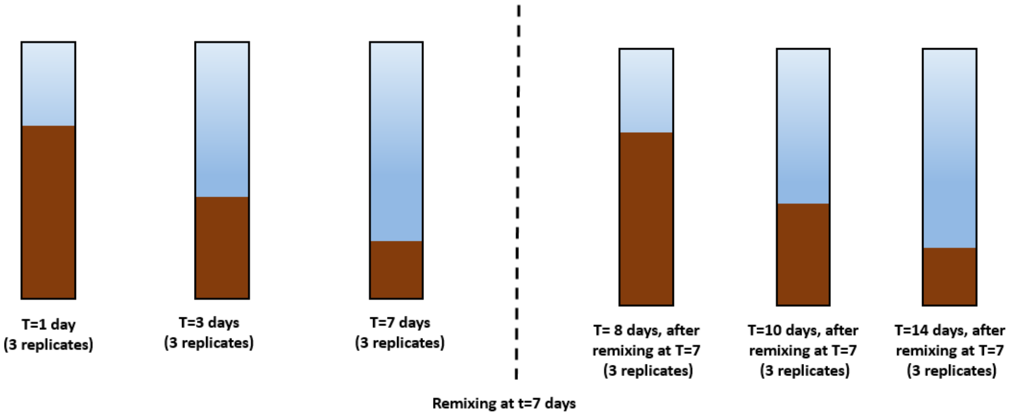

Figure 5. Settling column setup. Samples were taken after 1, 3 and 7 days. At t = 7 days, the columns that had not yet been sampled were remixed again with the supernatant water. Samples were also taken with the same frequency after this remixing (t = 8, 10 and 14 days)

2.2.2 Results and conclusions

The results show that mixing with freshwater does reduce the concentrations of ions present. They also show that there are differences depending on the degree of oxidation or valence of the ions. Monovalent ions such as sodium and chloride are released immediately at the moment of mixing. The concentration remains stable during the rest of the experiment. This behavior is the same in the supernatant as in the pore water (Figure 6). However, ions with higher valence such as sulfate are released progressively with time (Figure 7).

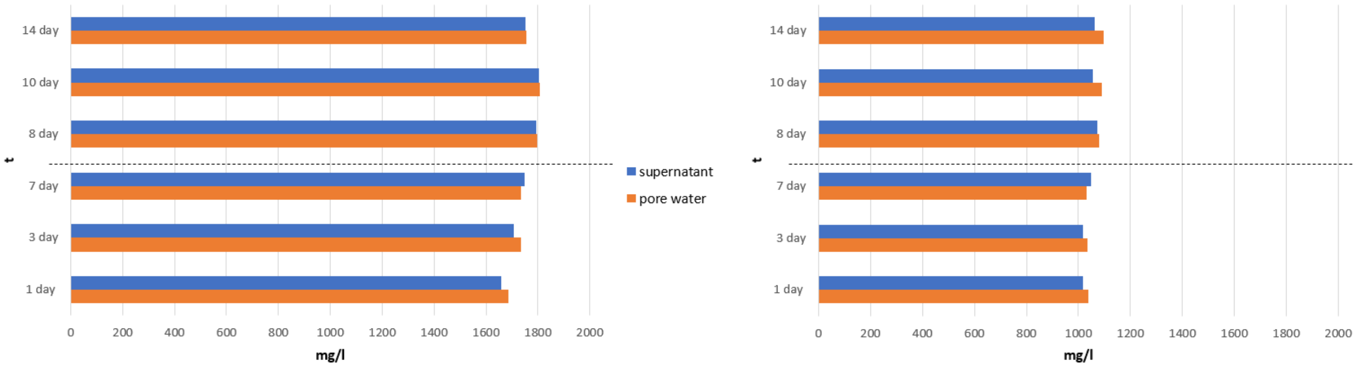

Figure 6. Evolution of the concentration of ions in the supernatant and pore water. Left panel: chloride. Right panel: sodium (Na+). The horizontal line marks the moment of remixing.

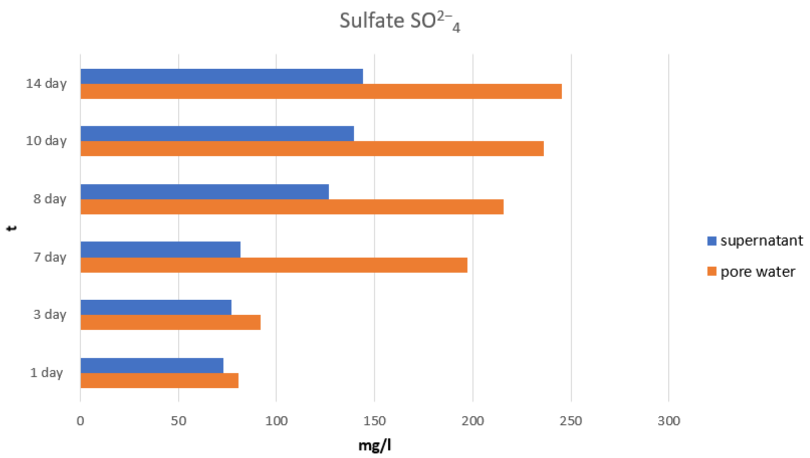

Figure 7. Evolution of the concentration of sulfate ions in the supernatant and pore water.

As it can be seen in Figure 6 and Figure 7, when an ion is released from the sediment, first it goes to the pore water and over time it is diffused to the supernatant. However, the measurements at different heights of the supernatant showed that stratification on the concentration of ions did not occur. This means that the concentration in the same through the whole supernatant.

The release of chloride and sodium occurs immediately after mixing. Therefore, with the goal of reducing the salinity, the best would be to remove the supernatant water as soon as the sediment particles have settled (i.e. non turbid supernatant water) and mix again with fresh water. Each mixing cycle decreases the salinity, especially if this mixing is done with new fresh water instead of the supernatant water. The optimum amount of mixing cycles depends on a number of project specific variables, including desired final salinity, salinity of dredge sediment and mixing water, density, mixing energy. Furthermore, mixing causes not only a reduction in salinity of the sediment, but also the release of nutrients. This has implications when the sediment is to be reused not for dike strengthening but for agricultural purposes, like in POL and IBP-VLOED.

Regarding the organic matter content, the present research showed that the quantification of organic matter for salty sediments is not straightforward. Salt hinders the water release and therefore higher temperatures than 105 °C are needed to remove completely the water present, which can lead to an overestimation of the organic matter content. After correcting for the amount of water that is released at temperatures above 105 °C, the total organic matter after mixing determined with TGA was 4.0 %. This correction was needed because the mass loss measured between 105 °C and 130 °C corresponded to water. The organic matter before mixing was determined by loss on ignition (European Standard, 2012) for four replicate samples, varying between 13.14 and 14.41 %. Despite the fact that the results clearly show that the mixing decreased the organic matter content, further analysis of the mass loss with temperature is needed with TGA to correct for eventual effect of water released at temperatures above 105 °C.

It is recommended to study the implication of the release of ions, of nutrients and the reduction of the organic matter content induced by mixing with fresh water on the ripening process and the quality and properties of the resulting soil. More information is needed about the optimal soil parameters needed for agricultural use. On one hand it is important to maintain all the nutrients and organic matter, but on the other it is also essential to reduce the salt content in order to avoid salinization of the groundwater and be available more different types of crops.

Additional results can be found in Appendix B.

2.3 Greenhouse gas emissions from dredged sediment deposits

The 2021 IPCC report has clearly indicated that current global warming is unprecedented in scale and speed and that it is induced by humanity, causing rapid changes in the atmosphere, oceans, cryosphere and biosphere. Within the Paris Agreement (2015) governments agreed to keep global warming at max 1.5 degree Celsius warming. In order to do so, all CO_2 emissions need to be limited to net zero CO_2 emissions. The European Union set out to reduce CO_2 emissions by 55% in 2030 and to be carbon neutral by 2050. The Dutch government aims to reduce CO_2 emissions by 50% in 2030 and net zero in 2050. Many sectors have adopted these goals. This section focusses on ecosystem- and sediment-related GHG emissions from hydraulic engineering activities.

This section of the report and this TKI-LLM project task is divided in two main activities: a literature review to highlight current status of knowledge related to ecosystem- and sediment-related GHG emissions (as opposed and in addition to machines and transport); and field-based measurements of GHG emissions on the Clay Ripening Kwelder deposit.

2.3.1 Literature review

Within the water sector, climate change is considered an urgent topic. Project owners (such as governments or private developers), have the ambition to be climate neutral by 2050. Current investments within the Hydraulic Engineering (HE) sector companies focus mostly on using sustainable energy sources, increasing carbon efficiency, creating sustainable solutions and carbon offset/credits.

In the Netherlands most tenders within the HE sector already include assessment based on the amount of carbon reduction or sustainability that can be achieved, using tools and certification via the "CO_2 prestatie ladder" and "DuBoCalc". Internationally the Greenhouse Gas Protocol[2] is used.

2.3.1.1 Ecosystem and sediment related emissions

There are components within HE projects that are currently not considered in the footprint and in most of the available tools, but have the potential to be a relevant source of GHG emissions. These components, such as dredging, relate to the disturbance of the natural system through HE activities and

[2] https://ghgprotocol.org/

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ultimately GHG emissions from the sediment that is handled. The extent of the impact on GHG fluxes from the natural system is currently however unclear, especially in comparison to background or to other man-made sources.(O'Connor et al. 2020; Dekker et al. 2014; Polrot et al., 2021).

At the time of writing no literature is available that reveals if and how dredging affects emissions from the affected extraction location, the deposition location, or the extracted material, let alone which dredging methodologies or deposition options are more efficient in terms of ecosystem restoration and sediment-related emissions.

2.3.1.2 Greenhouse gas emissions from ecosystem and sediment

Next to sand, silt and clay particles, dredged sediment contains organic matter, nutrients (like nitrogen and phosphorus) and potentially contaminants. Sediment holding organic matter has the potential to produce and release the GHG carbon dioxide (CO_2) and methane (CH_4) under certain conditions. It is well known that dredged sediment has gas production potential, as gas production is a risk when depositing soft sediment in landfills (Gebert et al. 2019; Gebert et al. 2006; Van Kessel & Van Kesteren 2002). In the past within Deltares and its predecessors much focus has been on modelling the risk of swell due to gas production, providing risk-management measures to prevent basins filled with soft-sediment from overflowing (Gebert et al. 2006; Van Kessel & Van Kesteren 2002). While this literature relates to almost two decades back, this remains the current state-of-the-art. To date, much remains unknown regarding the type, magnitude and rate of GHG production and release from deposited soft sediment, let alone how this relates to sediment properties and which measures can help reducing these emissions.

2.3.1.3 Greenhouse gas production potential

What we do know is that the quantity of organic carbon within a sediment will give an idea of the *potential* for GHG production, as it gives an indication of the maximum emission that is possible. Whether that emission will eventually materialize is subject to more debate.

Silt rather than the sand is an important determinant for the GHG production potential, as much as amount of nutrients, specifically nitrogen (ammonium, nitrate/nitrite) (Gebert et al.,2019). Within shallow lakes and river sediments, nitrogen and phosphorus are good proxies for GHG production, as was shown in the BlueCAN project (Schep et al. 2020). The quality of organic carbon, or the degradable share of organic carbon, is also relevant. Typically, older sediments contain organic carbon that is more degraded than young, freshly deposited sediment. Sediment depth correlates to sediment age, with deeper layers being older, and also there the relationship between age of organic carbon and degradability is found (Wijdeveld, 1999; Zander et al., 2020).

Furthermore, some conditions are known to limit production of certain GHGs. Sediments with a high salt (and especially sulfate) content like in marine environments, limit CH_4 production (Hebert et al. 2015; Kristjansson and Schönheit 1983). Therefore, many freshwater sediments tend to have higher expected emissions of the strong GHG CH_4. High oxygen availability prevents formation of CH_4, but allows for oxidation of organic carbon to CO_2, causing high CO_2 fluxes (Conrad et al. 2020a and 2020b). Last but not least, high iron (hydr)oxide availability is able to bind CO_2 as bicarbonate and thereby lower the CO_2 emission (Wijdeveld, 1999).

To determine the GHG production potential, degradation tests can be performed in the lab or can be estimated using models. Lab measurements involve incubation of sediment samples under aerobic and anaerobic conditions. To estimate the amount of GHG released for marine and freshwater sediments, several models have been made using sediment age, quantity of organic carbon present and degradability constants as important determinants for the GHG production potential (Gebert et al., 2006; Grasset et al., 2021; Lovelock et al., 2017; Middelburg, 1989; Wijdeveld, 1999).

Beside the geochemical characteristics of the sediment and its environment, project specific design and operations may have a large role on influencing how much of the potential emission is released.

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Selecting the optimum construction method, for example capping or underwater placement instead of upland disposal, can be important to limit GHG emission, or potentially improve sequestration.

2.3.1.4 Greenhouse gas flux from soft sediment land fills

The GHGs produced within soft sediment may at some point escape the sediment and reach the atmosphere. In the past, researchers at Deltares have studied how gas can escape soft sediment (Van Kessel & Van Kesteren, 2002) and when the critical threshold for GHG to escape from the sediment is reached. Produced gas will create bubbles that can only escape the soft sediment when these bubbles have enough pressure to migrate to the surface and by doing so create channels and cracks. How much gas needs to be produced for these cracks to form depends on the soft sediment characteristics. Deposited soft sediment may hold 25 up to 37% of gas prior to it escaping to the atmosphere (Van Kessel & Van Kesteren, 2002).Within Deltares models have been built within the numerical model Delcon based on formula by Middelburg et al. (1989) for organic matter decomposition in sediment. This has been applied in various projects amongst which Stryker bay, IJsselmeer, Ketelmeer and de Slufter (WL - Delft Hydraulics 2002, Wijdeveld, 1999).

2.3.1.5 Beneficial use of dredged sediment

Over the past years beneficial use of sediment gained ground, considering dredged sediment a valuable resource. By using dredged sediment to aid in the development of ecosystems that have a high potential to capture and store carbon, sediment can even become a carbon sink. The creation of natural island "Marker Wadden" in the Dutch Markermeer and the Indonesian mangrove forest restoration projects are two practical cases that demonstrated a significant increase in carbon captured in the sediment (Temmink et al. 2022, Veld, 2018). The Clay Ripening project showed limited GHG emissions and overall very little organic matter lost over the course of 3 years of ripening, indicating quite some organic carbon remains stored (Section 2.3.2). Beneficial use of dredged sediment and finding best practices to keep carbon locked in the sediment will help the HE sector to become carbon neutral by 2050. Furthermore, it offers economic potential for the carbon market, where the storage of carbon may be sold as carbon credits.

2.3.1.6 How to deal with ecosystem and sediment-related emissions in the future?

Ecosystem based carbon footprinting in marine engineering projects has been published (Dekker et al., 2014; Fiselier et al., 2015). Currently a protoype tool is developed that assesses the circularity of inland dredging activities including effects on ecosystem emissions (Besseling et al., 2021). This is created with the objective of helping the Dutch Water Authorities to dredge sediments more circularly. Other tools exist to assess the sustainability of civil construction projects, such as "DuBoCalc" and "CO2 prestatie ladder", both developed by Rijkswaterstaat[3]. These tools are beginning to incorporate ecosystem- and sediment-related GHG emissions, to some degree.

Efforts are made to get a grasp of ecosystem and sediment-related emission associated to HE activities. The "Programmatische Aanpak Grote Wateren" (PAGW) is a program within the Netherlands that aims to improve ecological quality of large water bodies within the Netherlands via restoration of estuarine dynamics and restoring shallow land-water transitions. The first exploration phase of the pilot study (proeftuin) for cost-effective and sustainable engineering of these shallow land-water transitions gave an important insight: next to GHG emissions from equipment used to dredge, the sediment itself and disturbance thereof may cause significant GHG emissions (Raadgever et al. 2020). Based on the dominant mechanisms that are associated with GHG emissions from soft sediment, the study also identifies several measures (e.g. the time of year that dredging takes place) that are likely to impact the size of this emission source.

[3] https://www.rijkswaterstaat.nl/zakelijk/zakendoen-met-rijkswaterstaat/inkoopbeleid/duurzaam-inkopen

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2.3.2 Experiments in Clay Ripening

As described in detail in the previous section, in dredging projects not only the combustion of fossil fuels by machines can be a source of GHG, but also the emission from naturally occurring organic material in the sediment may be a potential source. Likewise, beneficial use of sediment applications may provide solutions to sequestrate GHG. However, rigorous evidence and robust data for this is still missing.

This section summarizes the results of a GHG field measurement program carried out at the Clay Ripening Kwelder pilot site. This program is designed to measure GHG emissions from ripening organic-rich salty sediment dredged form the Eems-Dollard estuary in North Netherland, in the process to turn it into clay for local dike strengthening. This project intends thus to provide a contribution to the knowledge gap regarding potential GHG emission from or sequestration in sediment.

As mentioned in the literature review, GHG can be produced within sediment as a result of microbial degradation of the organic matter. Under certain conditions GHG can escape to the atmosphere. Little is known about how much GHG is released from organic-rich ripening salty dredged material and on the sequestration potential of this sediment when captured in the dike. It is important to underline that this investigation and the results, while of potential general validity, are specific to this application and the environmental conditions of the salt marsh sediment near the project location in the North of the Netherlands.

Within the EcoShape consortium, Deltares has carried out a research project in collaboration with Wetlands International and Oregon State University, USA. The specific goals of this study were to:

- Determine emissions of GHG (carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O)) during ripening of dredged material in the Clay Ripening Kwelder sedimentation basins; and
- Evaluate factors that influence these GHG emissions.

2.3.2.1 Results

After filling the ripening plots with sediment from December 2019 to March 2020, GHG emissions were measured in April and June 2020 (Figure 8).

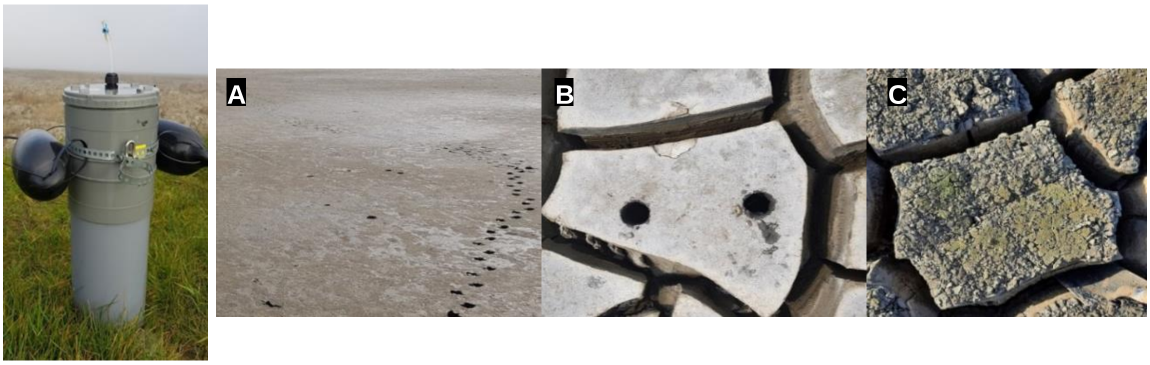

Figure 8. Left: cylindrical respiration chambers for sampling GHG in the field. Right: pictures of the development of the ripening clay week 5 (A), week 13 (B), week 35 (C).

Over the course of these two months GHG emissions (CO_2 and CH_4) from ripening salty estuarine sediment was very low: CO_2 and CH_4 concentrations in gas chambers at the sediment were insignificant compared to control chambers at the adjacent salt marsh. One of the reasons for this was probably the high concentration of sulfate in the sediment, which can lead to the inhibition of methane production. Another factor that might explain the low GHG emissions observed is slow oxygen transport into and slow GHG transport out of the ripening clay. Increase in salt and sulfate concentration upon drying and limitation of transport through the clay will further limit GHG emissions upon further ripening. The role of salt in limiting GHG emissions from sediment was supported by laboratory experiments of CH_4

emissions from sediment in closed vessels: freshwater sediment samples showed significant CH_4 emissions, whereas estuarine sediment samples did not.

In addition to the experimental data, the decrease in organic matter (OM) content of the sediment was used to estimate cumulative GHG emissions over longer timescales (months), assuming that all OM would have been oxidized to GHG. The calculated emissions, while higher than measured, remain below the emissions estimated for transporting clay from Belgium to be used to build the same dike at the Kwelder location alone.

2.3.2.2 Recommended additional work

We recommend expanding the GHG emission study to a range of sediments that are typically dredged and deposited on land. This will help to bring perspective in ripening of dredged sediment and accompanied emissions. It will also help to objectively determine the extent of GHG emissions from sediments with respect to other emission sources within the project and as background. A range of aquatic sediments varying in salt concentrations (freshwater, brackish, salt) would allow to study the effect of salt and sulfate. A range of organic matter (OM) content and age of this OM would allow to study whether OM ripening occurs once the sediment is deposited on land, and how this affects GHG emissions.

In this study the focus was limited on emissions of the ripening sediment. However, there are many process steps prior to the ripening period of the sediment that were not considered. It would be good to study GHG emissions all the way from pre-dredging up to the moment the ripened clay has been implemented in the dikes. The pre-dredging scenario gives an indication of a reference GHG emission to compare the other emissions too. Pre-dredging or natural emission are particularly important to provide the correct perspective on how significant the effective contribution of dredging, or more generally, of human intervention is with respect to the naturally occurring GHG emission. Should GHG emissions from sediment be proven significant, this data should be incorporated into a tool that is able to calculate (predict) C-emissions, C-capture and C-storage for these types of dredging activities.

2.3.2.3 Dissemination

Using the results from this study, Wetlands International, Boone Kauffman from Oregon State University, USA and Deltares jointly made a calculation method for the GHG emission from the ripening process in the Clay Ripening, which was published in Terra and Aqua (see Appendix C). The calculation method presented offers a practical tool to estimate GHG emissions based on relatively simple input parameters (most notably organic matter content). This also offers a way to estimate effects of dredging or ripening conditions (e.g. freshwater vs. salt, availability of oxygen) and comparison to alternatives (e.g. alternative sources of sediment). It should be noted that the calculation method merely provides a start: many uncertainties still must be addressed, and the calculations must be supported by measurements.

2.3.3 Recommendations

The conclusions from the literature review and the Clay Ripening experiment show that there is a potential for release of GHG from sediment during HE works. However, the actual release depends strongly on parameters such as sediment characteristics and handling of the sediment (ways of dredging, ripening, ect). Also, to assess the importance of the release of GHG, it is crucial to make a proper comparison between alternatives. Therefore, additional research is needed to understand the actual extent of this release, when it takes place (in time and space) and how it relates to the other emissions from e.g. equipment during and after dredging and reclamation works. At this moment, some research is already taking place in e.g. the DUNAG program. General steps that can be taken when assessing potential GHG emissions of a project are:

- Define sediment types and locations (e.g. salt or fresh waters) with most potential for GHG release;

- Execute testing in field and lab on various sediment types during different parts of the dredging process and in various meteorological conditions;
- Plot results over time with regards to release and fixation (e.g. vegetation growth)
- Compare the results with other GHG emission sources during the project (e.g. context and significance);
- Compare results with other operational aspects in projects, like transport of clay towards site if beneficial use of dredged sediment will not be possible.

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3 Dissemination and networking

As part of the scope of this project, various communication and networking activities were carried out where the knowledge generated by this project, but also on the connected pilots, was disseminated. These included the proactive participation in and leadership of international network organizations, the publication in national and international publications and events, and the initiation of a Beneficial Use of Sediment table within EcoShape.

3.1 CEDA, PIANC, SedNet

CEDA, PIANC and SedNet represent the three most relevant professional network organizations for (North-)Europe in relation to sediment and beneficial sediment use. As part of the dissemination activities of this project, EcoShape led the CEDA Working Group on Beneficial Sediment Use with Luca Sittoni as chair, which in 2019 published an information paper on state of practice related to beneficial sediment use (BU), a position paper with focus on contamination and a case study public online library[4]. These publications collected about 40 case studies from more than 10 countries, mostly European. They structured the characterization of BU applications following function (Raw material, Remediation, Reclamation, Restoration and Resiliency) and technique (on land, in water a final or strategic location, natural trapping), underlying the key role of natural processes through BwN. The topics described in this report where recognizable in many of those project examples.. Regarding contaminants, the Position Paper makes a pledge for a risk-based management approach, beyond threshold values, as a necessary development to best manage contaminated sediments sustainably.

Following on the CEDA work, this project partially supported the co-chairing (Luca Sittoni) of PIANC WG 2014 on Beneficial Sediment Use started at the end of 2018 and near finalization. The report is due to be published in 2022. This report extrapolates the technical lesson learned into mainstreaming of BU identifying key barriers and especially enablers to increase the uptake of BU in sustainable water infrastructure projects. Key leveraging factors are identified in:

- Cost: from low cost single function to high value multi-function and multi-benefit;
- Connecting supply and demand: from offer driven (need to get rid of the sediment) to demand driven (need of sediment for BU);
- Partnership: proactive stakeholder engagement in projects to exploit multi-functions and benefits;
- Contamination: risk-based assessment to enhance safe use for human and nature.

In addition to these two literature milestones, this project supported the organization and the participation to various international events, often digitally, such as:

- SedNet 2021: keynote (Sittoni et al, 2021);
- SedNet and PIANC Navigating Climate Change Workshop[5]: chair;
- WodCon XXII, Sittoni et al. (2019).

3.2 The USACE Atlases

All pilots part of the 2017 Living Lab for Mud initiative were featured in the USACE Atlases (Bridges et al., 2018 and Bridges et al., 2021) as example of BU and BwN projects. This TKI-LLM project supported the realization of the text included in these publications

[4] https://dredging.org/resources/ceda-publications-online/beneficial-use-of-sediments-case-studies
[5] https://navclimate.pianc.org/events/events-archive/navclimate/pianc-navclimate-working-with-nature-workshop

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3.3 The EcoShape Beneficial Use of Sediment Table

As stated in the introduction and as the results presented in this report confirm, BU is an important innovative practice for the Netherlands and for achieving international ambition globally. Sediment is further the foundation of effectively all NbS in water infrastructures. BU solutions help therefore application of NbS at landscape scale, which is the current mission of EcoShape – Building with Nature.

Building on the legacy of the ongoing projects and with the intention to develop larger and larger BU knowledge development and project opportunities, EcoShape started the Table Beneficial Use of Sediment in March of 2021. This table is a platform for EcoShape and non-EcoShape partners to share ideas, opportunities, ambitions to advance practice related to BU. This table includes several EcoShape projects related to BU. The TKI-LLM is one of these projects. The TKI-LLM is therefore an important contributor to the technical content of the table. At the same time, the table offers an excellent opportunity to communicate and disseminate the results to the projects directly to professionals deeply involved in BU and BwM.

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4 Upscaling BwM knowledge

In addition to developing integrated practical knowledge and lesson learned and to support various dissemination and networking activities, this project directly and indirectly supported spin-off activities. The most relevant include:

- Fase 1 of the Meegroeidijk project, to study the feasibility of the Meegroeidijk concept, which consists of applying thin layer of locally available fluid or ripened mud directly on existing dikes for maintenance (e.g. filling cracks) or strengthening (e.g. widening or heightening). The TKI-LLM supported EcoShape contribution to this project;
- The NWO Hedwige-Prospectpolder project, which studies how management realignment can be used as a NbS for flood safety. The TKI-LLM supported the EcoShape expert contribution to this project for the first year.
- Indirect contribution to the demonstration project Brede Groene Dijk, the pilot POL and to the Program VLOED in the Eems-Dollard area. While these projects are not directly supported by this TKI-LLM project, they make direct use of the knowledge developed by this project upscaling it to market projects (POL), dikes reinforcement programs (BGD) and regional programs (VLOED).

4.1 The Meegroeidijk

The Meegroeidijk (MGD - Growing Dike) is a concept where thin layers of dredged clay-rich material are deposited directly on an existing dike located in the vicinity of the dredging location. A dike is thus strengthened or repaired via more frequent and less impacting interventions using locally available material (Figure 9). This is a concept inspired by old techniques to build dikes but perfectioned utilizing current state-of-the-art knowledge. Depending on the thickness of the layer, vegetation may survive and grow through it. Worms feed on the organic material in the layer, thereby improving the clay quality. Specific seeds may be dispersed to develop the grass to improve flood safety and enhance the esthetics of the dike (e.g. flowers). The MGD concept is expected to contribute to:

- Flood safety: increasing the resilience with respect to sea-level rise and peak freshwater river discharges;
- Cost reduction: for the cumulative cost of dike reinforcement, maintenance and dredging;
- Circularity: beneficial use of locally available dredged sediment;
- Climate and sustainability goals: reducing the CO_2 and NO_x footprint (less transport and vegetation-based fixation of NO_x).

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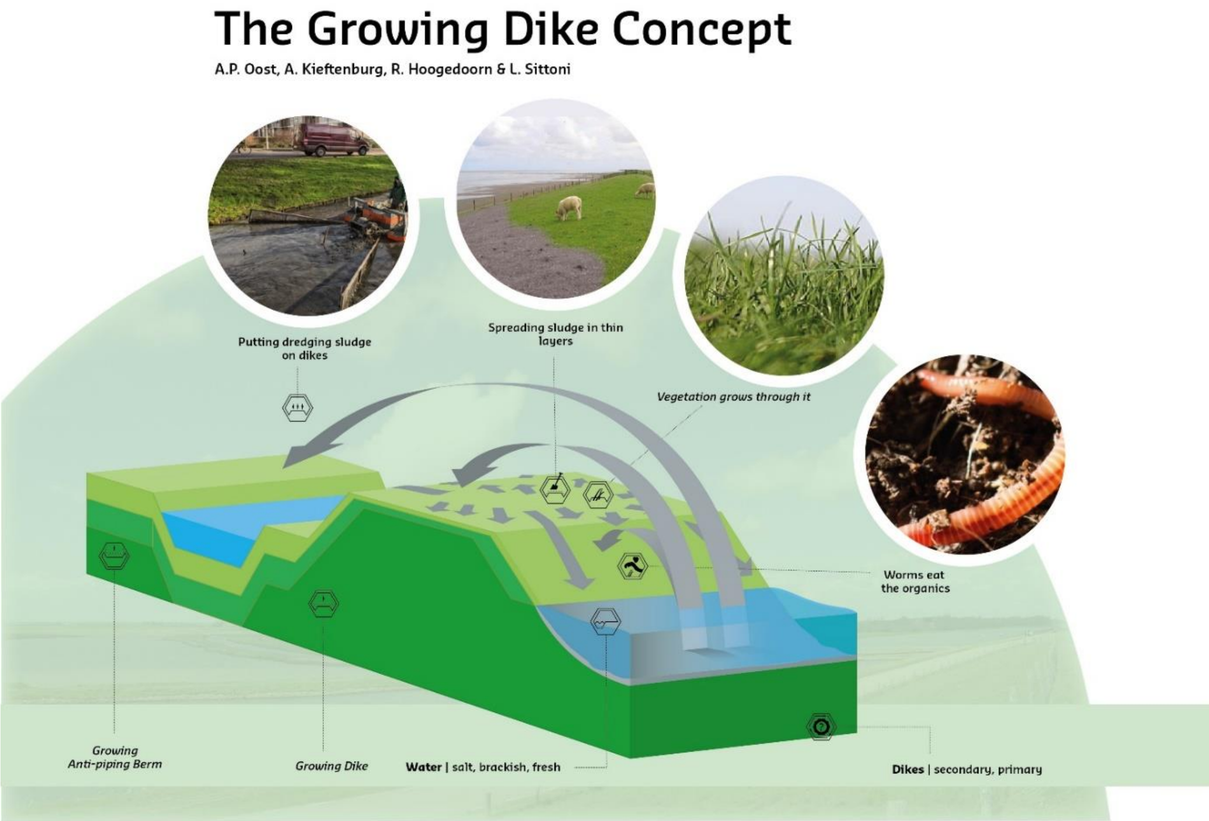


Figure 9. Illustration of the MGD concept.

This project is divided in different phases. After an initial development of the concept a first phase was carried out in 2020 and 2021 to evaluate technical and financial feasibility and to scope out the trajectory till implementation. Based on the results of Phase 1, a second phase is currently under scoping to test the concept on specific pilot locations. Phase 1 was setup as a collaborative research project between the Foundation for Applied Water Research of the Dutch water authorities (STOWA), the Dutch water authorities Rijnland, Brabantse Delta, Noorderzijlvest, EcoShape, the EcoShape partners Deltares, Wageningen Marine Research, Royal Haskoning DHV, Witteveen en Bos, van Oord and Hogeschool van Hall en Larenstein. All partners co-invested financially. This TKI-LLM project provided the financing from EcoShape, to match the contribution of STOWA, the water authorities and all other EcoShape partners.

A significant part of Phase 1 was dedicated to proactively involve different stakeholders in the project, especially the water authorities. This resulted in the partnership mentioned above. Further, the consortium investigated the technical and financial feasibility of the concept, which resulted in the report attaches as Appendix D. Two types of concept and two applications where developed:

1) Direct deposition of low-density dredge sediments, hydraulically;
2) Deposition of denser or partially ripened sediments, mechanically.

The two applications consist application on the dike for strengthening or repair (e.g. cracks), or application at the foot at the dike against piping (Figure 10).

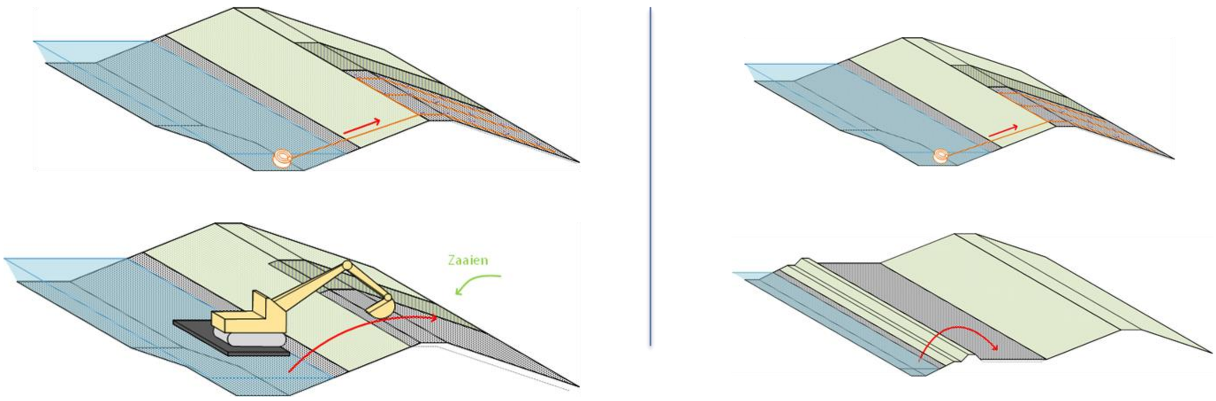
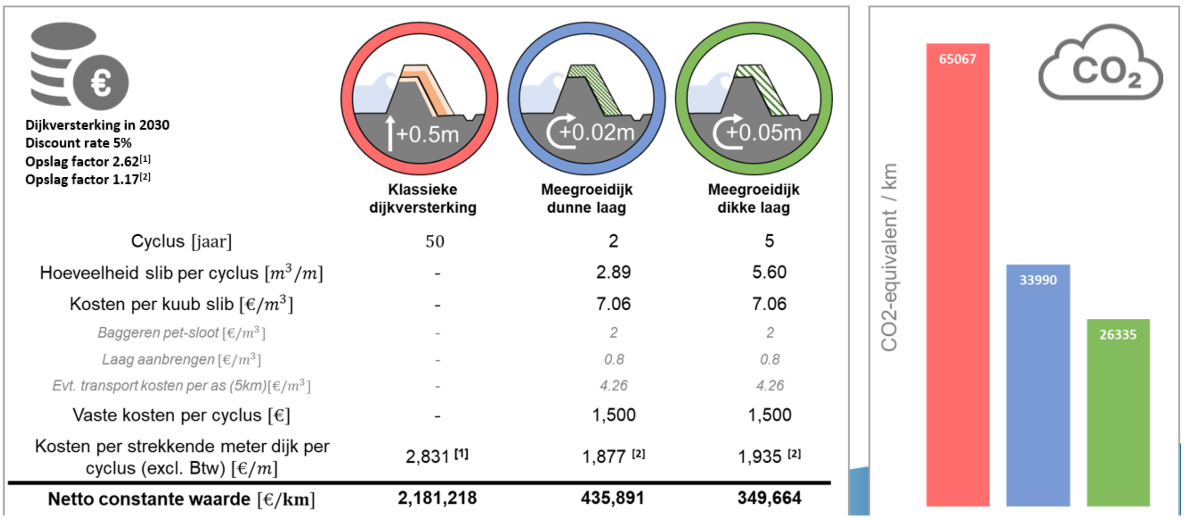


Figure 10. The MGD concept (left), hydraulic (above) and mechanical (below) deposition, and potential applications (right), strengthening or repair (above) and piping (below).

These two concepts appear to be technically feasible when enough dredge material source of the appropriate quality is available in the vicinity of the dike. Many remain the open questions regarding, above other, the specific characteristics of the sediment (e.g. particle side distribution, density, quantity), behavior of the sediment on the slope during deposition and its development in time, survival and growth of vegetation.

The general business model developed during the feasibility study indicates that the MGD may be cheaper than traditional dike construction, when dredging and construction activities can be coupled efficiently, and re-handling of the sediment and transport distance are kept to a minimum. Under the same conditions the MGD concept appears to have a smaller carbon footprint than traditional dikes constructions (Figure 11).



	Klassieke dijkversterking	Meegroeidijk dunne laag	Meegroeidijk dikke laag
Cyclus [jaar]	50	2	5
Hoeveelheid slib per cyclus $[m^3/m]$	-	2.89	5.60
Kosten per kuub slib $[€/m^3]$	-	7.06	7.06
Baggeren pet-sloot $[€/m^3]$	-	2	2
Laag aanbrengen $[€/m^3]$	-	0.8	0.8
Evt. transport kosten per as (5km) $[€/m^3]$	-	4.26	4.26
Vaste kosten per cyclus [€]	-	1,500	1,500
Kosten per strekkende meter dijk per cyclus (excl. Btw) $[€/m]$	2,831 [1]	1,877 [2]	1,935 [2]
Netto constante waarde [€/km]	**2,181,218**	**435,891**	**349,664**

Figure 11. Illustration of the MGD business case in comparison with standard dike strengthening (left), with carbon footprint evaluation based on emissions from equipment / transport only (right).

Given the outcome of Phase 1, the project will continue in 2022 with more in-depth investigation of the technical open question and a more detailed business model, on specific test locations. It is indeed likely that each of the three water authorities will provide a specific location to further test the concept in the field.

While this TKI-LLM stopped in 2021, it made Phase 1 of the MGD possible, generating the spin-off for this concept towards potential full-scale implementation.

4.2 NWO Hedwige Polder

In the coming four years, the Hedwige-Prosperpolder in the Schelde estuary will be reopened for nature restoration. This creates opportunities, within a binational Dutch-Belgian consortium, to experiment with the existing dike and to perform targeted dike breach experiments and breach monitoring. This creates also the opportunity to use the BwM and NbS knowledge and practical experience described in this report as a spin-off for application in a different, while very important, direction.

This NWO project is led by the Technical University of Delft. This TKI-LLM project supported the first year of EcoShape contribution to this project. While the project is still at its incipit and results are not yet available, it is here reported for completeness. The text in this section is largely taken from the NWO proposal submission on the NWO website.

Technically speaking, this project exploits the opportunity to investigate a newly described, potentially valuable contribution of vegetated foreshores to flood safety: the restriction of dike breach extent and thus of flooding volume in the case of failure of the dike. Fostering marsh development in front of realigned dikes could improve safety more than hitherto thought. Not only does it reduce dike failure probabilities, it may also restrict the consequences of failures. Even though this is not the primary goal of the Hedwige Prosperpolder realignment, this Living Lab will study how management realignment can be used as a NbS for flood safety. The contribution of vegetated foreshores will be modelled to breach development, calculating its contribution to reduction of risks, and validating the model itself using the breach experiment. This project will also study the conditions for, and rates of, vegetation and soil strength development in front of realigned dikes. Novel designs and maintenance schemes for realigned dikes will be explored, connected to a vegetated foreshore. Finally, this project will study how people experience physical changes in the landscape in terms of place attachment: will they be reconnected to the changed landscape when properly informed on the new role of this landscape in ecosystem development and safety enhancement?

The project consortium is composed of engineers, ecologists and social scientists with a strong track record in multidisciplinary co-operation. It is externally supported by national and regional water authorities, contractors and engineering companies. It is ideally situated to translate new knowledge into operational procedures and incorporate this into the education of future coastal professionals.

4.3 Application of BwN knowledge in the Eems-Dollard

The Eems-Dollard is one of the last two natural estuaries in the Netherlands. The still intact connection between river and sea makes it a special habitat for unique flora and fauna. The same region is characterized by important economic activities for the country, such as ports, industry and agriculture. Relatively large human settlements are also present in connection to these economic activities but also as renown centers for tourism and recreation. A key sign of the stride between natural activities and natural ecosystem is the increase in the turbidity level in water in the Eems-Dollard, due to significantly decreased sedimentation capacity of the estuary. This appear to be mainly caused by the combination of the need of deeper and deeper navigation channels (i.e. dredging) to facilitate access to ever bigger ships and land reclamation of large parts of the estuary which provides little opportunities for natural siltation. Research says that a potential solution can be reached by structurally reducing the amount of fine sediment in the estuary[6].

As part of the Eems-Dollard 2050 program, various pilots have been initiated and partially executed, to assess the technical, financial and legal feasibility of various solutions to beneficially use Eems-Dollard sediments. EcoShape and EcoShape partners play an important knowledge development role in several of these projects. These include:

[6] https://www.ee-eemsdelta.nl/assets/pdf/dossiers/natuur-en-landschap/Eindrapport%20MIRT-onderzoek_Eems-Dollard.pdf

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- The Clay Ripening, where sediment dredged from the Eems-Dollard is ripened into clay for dikes[7,8]. Two types of locally available sediments are let ripen in dewatering basins for three to four years: sediment from the Delfzijl harbor channel and from the saltmarsh Breebaart. During these three years the sediment needs to decrease its water, salt and organic content to meet the requirements to be used for dikes construction. The sediment is deposited in dewatering basin in one or two layers for a total initial thickness between 1.5 and 2 m of dredge material. The sediment is then let ripen for three to four years. During ripening some reworking were carried out during the summer to facilitate exposure of the clay to the atmosphere and rain. At the time of this report, after nearly four years of ripening, the water content appears to reach the target level, especially when sufficiently reworked. The salt and organic content are also decreasing, even if slower than initially thought. These tend to decrease especially after two years, when before they remained about constant. This is true when salt content is measure as concentration in the pore water, not in total volume, which does decrease significantly from the beginning. This TKI-LLM project leveraged on the data and knowledge of the Clay Ripening extending its modeling study to evaluate different scenario's and collecting the lesson learned to derive generally applicable guidelines.
- The Research for the Suitability of Delta clay[9,10] (OGD), which studies the workability and the resistance again erosion of the clay produced with the Clay Ripening project when applied to the Brede Groene Dijk. This project is indeed necessary to evaluate the performance of clay that is different in properties from standard clay (i.e. higher salt and organic content) utilized to build a dike with lower slope that ordinary dikes (1:7 instead than 1:5 to 1:3), which falls outside the applicability range of current erosion models. This project included the construction of a small test dike, several small-scale laboratory experiment and probabilistic computations and two field scale tests in the Deltares Delta Flume. These activities demonstrated the workability of Clay Ripening clay in dikes if treated with a specific work method, consisting of construction in subsequent relatively thin (20 – 40 cm) layers. They also demonstrated the resistance to wave erosion of a dike constructed with a 1:7 slope with Clay Ripening clay, effectively validating the design of the Brede Groene Dijk. The TKI-LLM project did not directly contributed to this project, but indirectly through the ripening knowledge which is instrumental to deliver the construction material for this dike.
- The demonstration project Brede Groene Dijk[11], during which a 600 m Brede Groene Dijk will be built (in 2022) and monitored for the following three years. This dike will be built above the current dike, making it broader. This broader dike should be sufficient to fulfil the strengthening dike requirement to withstand sea level rise and climate change predictions. If this demonstration will be successful, the entire Dollard Dike South of Delfzijl till the border with Germany will be broadened this way. The demonstration project will be built with three types of clay coming from the Clay Ripening: the ripened Delfzijl and the Breebaart clay and a clay excavated from the tidal area in front of the future location of the dike (Klutenplas clay) and following the designed tested in the Delta Flume by the OGD project. Also in this case, the TKI-LLM project only have indirect, yet critical, connection through the ripening knowledge.
- The Pilot Raising Agricultural Land (POL) which tests the feasibility of turning dredge Eems-Dollard sediment, dredged from the harbor of Eemshaven, into productive agricultural land. A layer of about 80 cm of dredge sediments is deposited on four hectares subsiding low-lying agricultural parcel. After 3 years the dredge sediment is expected to turn in about 40-centimeter layer of agricultural land, with several benefits, including better soil quality, counteraction of subsidence and decrease of oxidation of the underlying peat layer. Very importantly, this project also tests the feasibility and efficiency to desalt salty dredge sediment. After dredging and before

[7] https://eemsdollard2050.nl/project/pilot-kleirijperij/
[8] https://www.ecoshape.org/nl/pilots/kleirijperij/
[9] https://www.hunzeenaas.nl/projecten/brede-groene-dijk/onderzoek-geschiktheid-deltaklei/
[10] https://www.deltares.nl/nl/nieuws/dijk-van-circulaire-klei-getest-in-deltagoot/
[11] https://eemsdollard2050.nl/project/brede-groene-dijk/

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deposition this sediment is mixed with fresh water to decrease the salt concentration. Low salt concentration is indeed critical for productive agricultural land. This TKI-LLM directly leveraged and contributed to this project. The desalination task of the integrating research (Section **Error! Reference source not found.**) utilized sediment coming from this pilot in the tests. The student and the HAN university staff could also benefit from visiting the pilot and interacting with the staff working on the pilot. Vice versa, the knowledge developed in this task of the TKI-LLM project is delivered back to the POL project staff and clients to be directly used in the project as applicable.

- The program Improving Agricultural Soil through Raising it with Sediment from the Eems-Dollard[12] (VLOED) studies the technical and socio-economic feasibility of scaling up the technologies demonstrated in the pilots Clay Ripening and POL on regional scale. Three representative scenario's are evaluated: using ripened sediment for raising agricultural land (as in POL), using ripened sediment as clay for dikes (as in the Clay Ripening) and beneficially extracting sediment through natural tidal processes. This project focus significantly on the governance, legislation and economic aspects of upscaling, especially the proactive engagement of local stakeholders to develop solutions that are truly embedded in and supported by the proactive participation of the local community. The TKI-LLM is not directly linked to this project, however it is evident how this project benefits from, in fact is founded on, the knowledge developed in the single pilots and the integrated knowledge developed and disseminated by this TKI-LLM project.

[12] https://eemsdollard2050.nl/project/vloed/

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5 Acknowledgment

This project and this report are based on the extensive research work carried out by a number of EcoShape partners. Each report attached as appendix and the authors of these reports are integral part of this collaborative effort.

EcoShape partners involved in this project include Deltares, HKV, Van Oord, Boskalis and Wetlands International. In addition to these partners, other EcoShape and non-EcoShape partners participated actively in activities correlated to this project: Hogeschool van Arnhem en Nijmegen, Provincie Groningen, NETICS (KIEM project), Wageningen Marine and Research, Witteveen en Bos, Royal Haskoning DHV and Hogeschool Van Hall Larestein (Meegroeidijk Fase 1) and TUD (NWO – Hedwige Polder).

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A Appendix – Ripening of dredge sediment

1. Literature review and conceptual model for the ripening of mud (memo)
2. Conceptual model description (ppt)
3. Consolidation and ripening modelling of the Clay Ripening pilot (ppt)
4. 1DV ripening model development (ppt)
5. Practical guidelines for BwM projects (memo)

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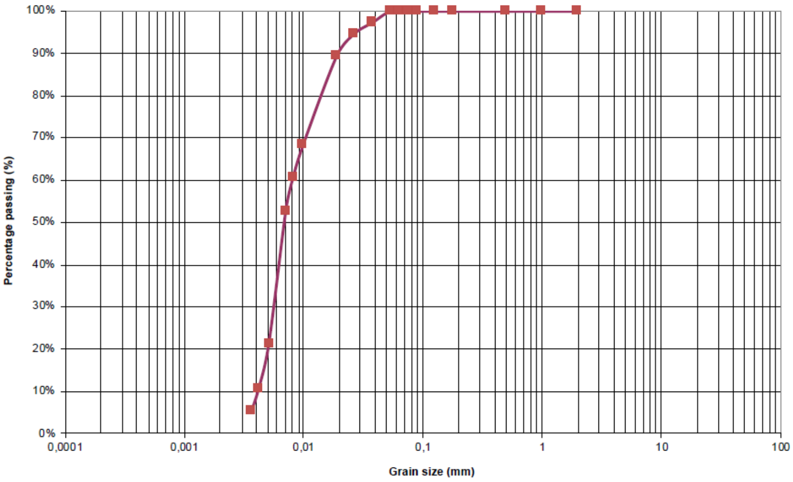
B Appendix – Desalinating dredge sediment

In this appendix, additional experimental results from the “Desalination of Dredged Sediment for Delta Protection project" are presented.

B.1 Particle size distribution

The particle size was determined using a hydrometer and by dry sieving according to the British Standards Institute (1990). The results are shown in Figure 12.



Grainsize (mm)	Passing (%)
2,000	96,86
1,000	96,37
0,500	96,16
0,180	94,92
0,125	91,50
0,090	91,40
0,063	87,56
0,07563	32,01
0,05348	32,01
0,03788	31,17
0,02683	30,32
0,01904	28,64
0,00996	21,90
0,00817	19,37
0,00711	16,85
0,00513	6,74
0,00421	3,37
0,00366	1,68

Figure 12. Particle size distribution of the sediment from the POL pilot studied in the larger “Desalination of Dredged Sediment for Delta Protection project"

B.2 EC measurements

The EC measurements are shown in Figure 13 and Figure 14. The fact that the EC measurements 24 h after initial mixing and remixing at t = 7 days are higher (they are outliers in the figure below) suggests that at the moment of mixing and the hours afterwards more salts are in the supernatant. The results also show the slow progressive increase of salt content over the days caused by diffusion of ions through the sediment.

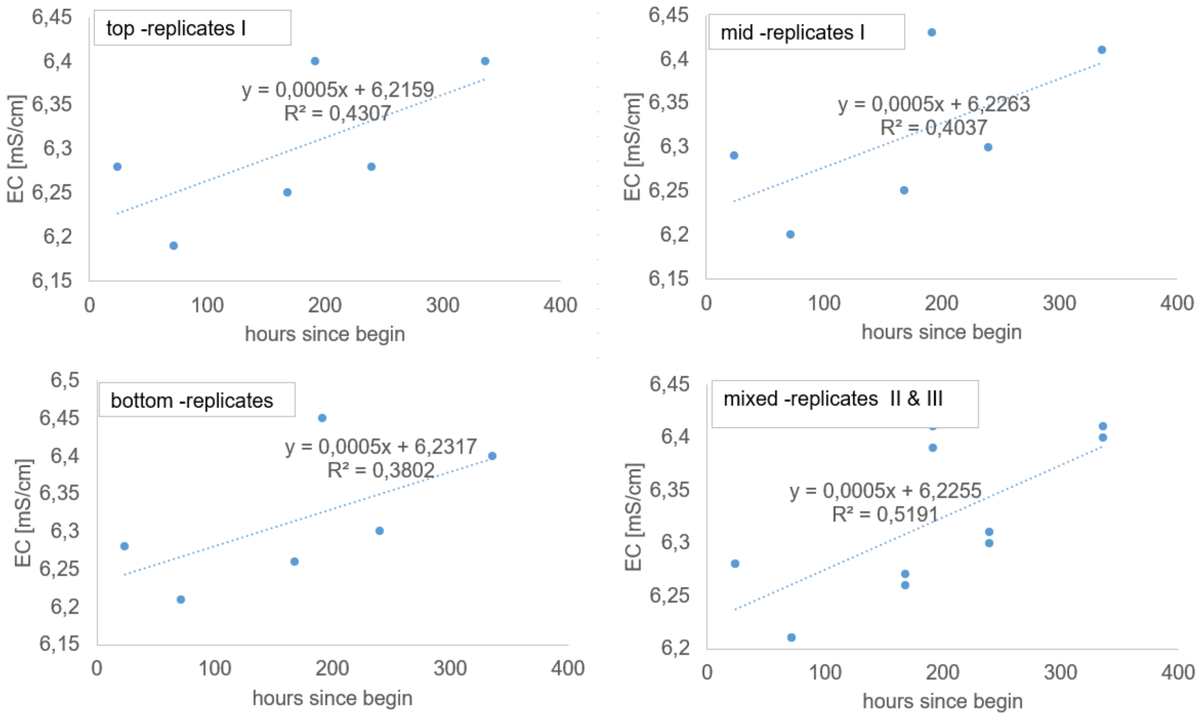


Figure 13. All EC measurements performed in the supernatant samples at different heights in the column (for the columns of the replicates number I) and of a homogeneous sample of the whole supernatant (for replicates II and III), including the trend line. The measurements performed 24h after mixing and remixing are outliers to this figure.

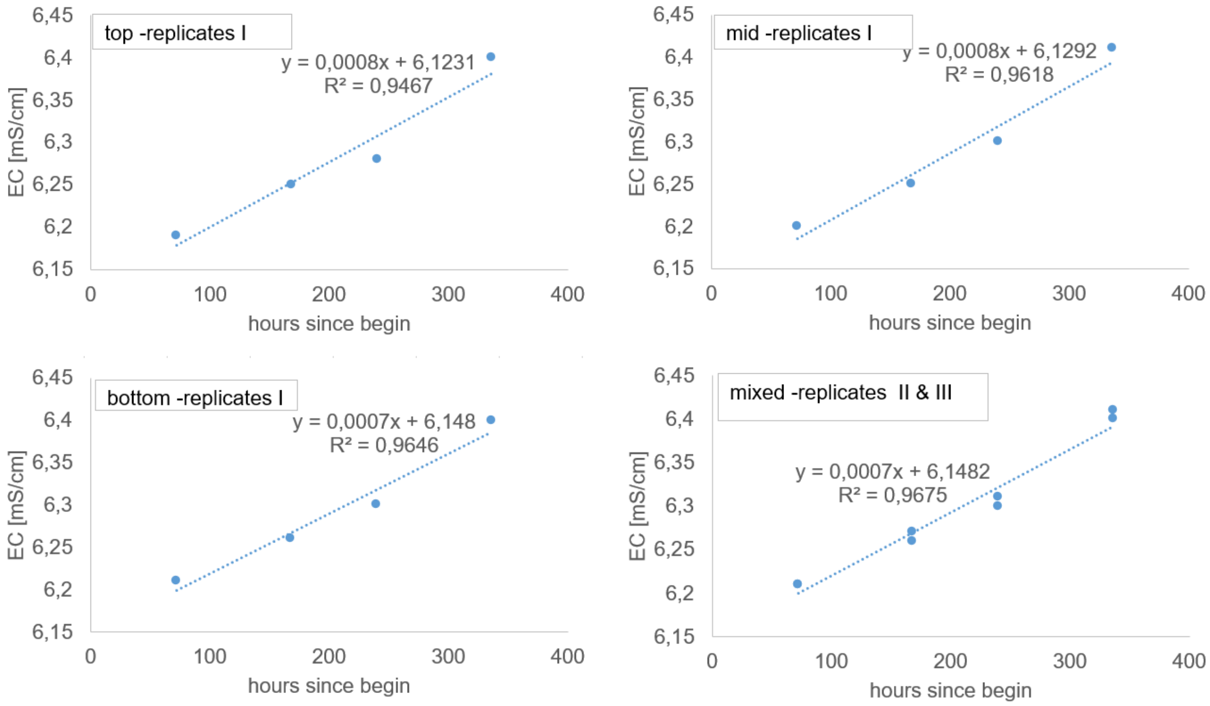


Figure 14. EC measurements except the measurements 24 h after mixing (or remixing) and the trendline. EC measurements performed in the supernatant samples at different heights in the column (for the columns of the replicates number I) and of a homogeneous sample of the whole supernatant (for replicates II and III), including the trend line.

B.3 Settling behavior of the sediment

The sediment-water interface was monitored for all the columns. Figure 15 shows an example for three columns that were remixed. It can be observed that after the first mixing cycle, some small differences

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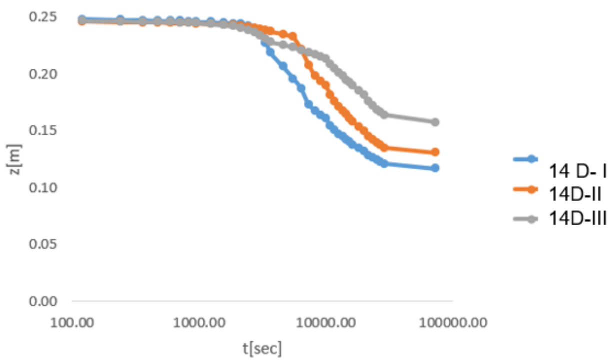
on the flocculation (horizontal first part of the curve) and the initial settling velocity are observed. However, with the second cycle of mixing, all the replicates perfectly overlapped. This is remarkable and occurred for all the remixed columns. An explanation for the larger differences between replicates at the initial phase of the column experiments could be the larger initial different in salinity between the solvent (tap water) and the solute (dredged sediment) at the first mixing and settling cycle. However further research is needed to conclude.



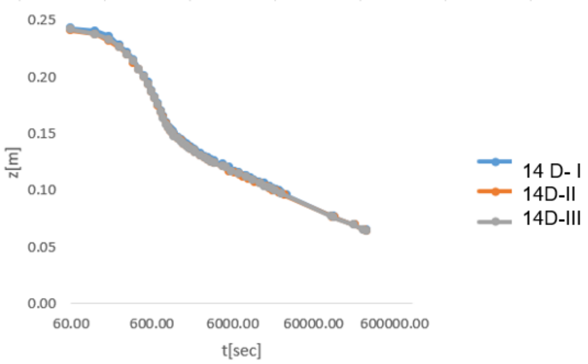


Figure 15 Left: evolution of the sediment-water interface since initial mixing for three replicate columns from day 1 till day 7. Right: evolution of the sediment-water interface of the same columns from day 8 till day 14, after remixing at t=7.

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C Appendix – Greenhouse gas emissions from dredge sediment deposits

1. Greehouse gas emissions from the clay ripening pilot “Clay Ripening” (report), including:
    - Litterature review (memo)
    - Terra & Aqua article (article)

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D Appendix – Meegroedijk

1. Meegroeidijk Phase 1 report

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