THE LIVING LAB FOR MUD: INTEGRATED SEDIMENT MANAGEMENT BASED ON BUILDING WITH NATURE CONCEPTS

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Abstract: World-wide the turbidity of many rivers, estuaries and shallow seas is increasing, leading to degradation of water quality and growing siltation. Large volumes of dredged sediments are disposed and lost offshore, while coastal regions and river banks are eroding, exposing towns to more recurrent flooding. A huge amount of sediment is trapped in reservoirs behind dams, reducing their storage and flood mitigation capabilities. These are all indicators that smart and integrated sediment management is necessary. At the same time, coastal development activities demand for large quantities of sediment as building material, with many areas of the world characterized by fine sediments (mud), especially in large river delta regions.

Integrated sediment management approaches leveraging on Building with Nature (BwN) concepts represents a potentially powerful solution to these enormous world-wide challenges and societal needs. With this in mind, EcoShape initiated the Living Lab for Mud (LLM), an initiative that aims to develop integrated knowledge and technologies to improve understanding and implementation of management, use and reuse of (fine and soft) sediments often linked to the reinforcement, safety and restoration of coastal ecosystems (e.g. salt marshes and mangroves) or land reclamation.

The LLM consists of a series of pilot projects within and outside the Netherlands, which integrate the various aspects and processes of sediment management: from sedimentation and resuspension, to fate and transport, to consolidation and strength development. The LLM integrates these physical processes with biota and socio-economic aspects, in order to develop feasible, applicable and sustainable BwN based solutions. Pilots include strategic sediment disposal to naturally nourish coastal mudflats (i.e. Mud Motor, The Netherlands), enhancing sediment trapping to encourage mangroves restoration and coastal aggradation (i.e. Demak, Indonesia), and ripening of fine dredged sediments for production of building material (i.e. Kleirijperij, The Netherlands).

This presentation will introduce the LLM initiative and give an overview of these pilot projects.

Key words: sediment management, Living Lab for Mud, Building with Nature, knowledge program, fine sediment

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1 SEDIMENT ABUNDANCE OR SHORTAGE: WORLD-WIDE CHALLENGES

Flooding threats in low-lying countries and deltas are increasing because of: climate change and associated sea level rise, which makes the hydraulic forcing on the land or its sea defences larger; subsiding land by settling soils (increased by drainage and groundwater usage), which makes the vulnerability to flooding higher; and sediment deficits or abundance due to increased human interference with these sediment rich (eco)systems. A significant contribution to the shift in sediment regimes, which determines abundance versus shortage, can be attributed to human interventions such as the creation of hydraulic structures, deepening of estuaries (Winterwerp and Wang 2013, Winterwerp et al. 2013) and damming of rivers (Vörösmarty et al. (2003) and Figure 1) which cause major changes to the stability of these delta systems.

The shift in the sediment regime confronts societies living in deltas with major challenges: degradation of water quality, hindering of ecosystem performance, and increasing cost for dredging and transport of sediments in surplus. Abundance of sediment appears for example as large deposits of fine sediment layers in reservoirs behind dams, in dynamic siltation patterns around hydraulic structures and an overall increase in suspended sediments in the wider delta and coastal zone waters. Sediment shortage shows, for instance, as increased erosion of coastal regions and river banks, and exposure to recurrent flooding. Large contributors to the reduced sediment availability in the delta and coastal zone are upriver damming and reservoir. Vörösmarty et al. (2003) have mapped many large reservoirs in the world which traps sediment from transport towards coastal waters (see Figure **1**).

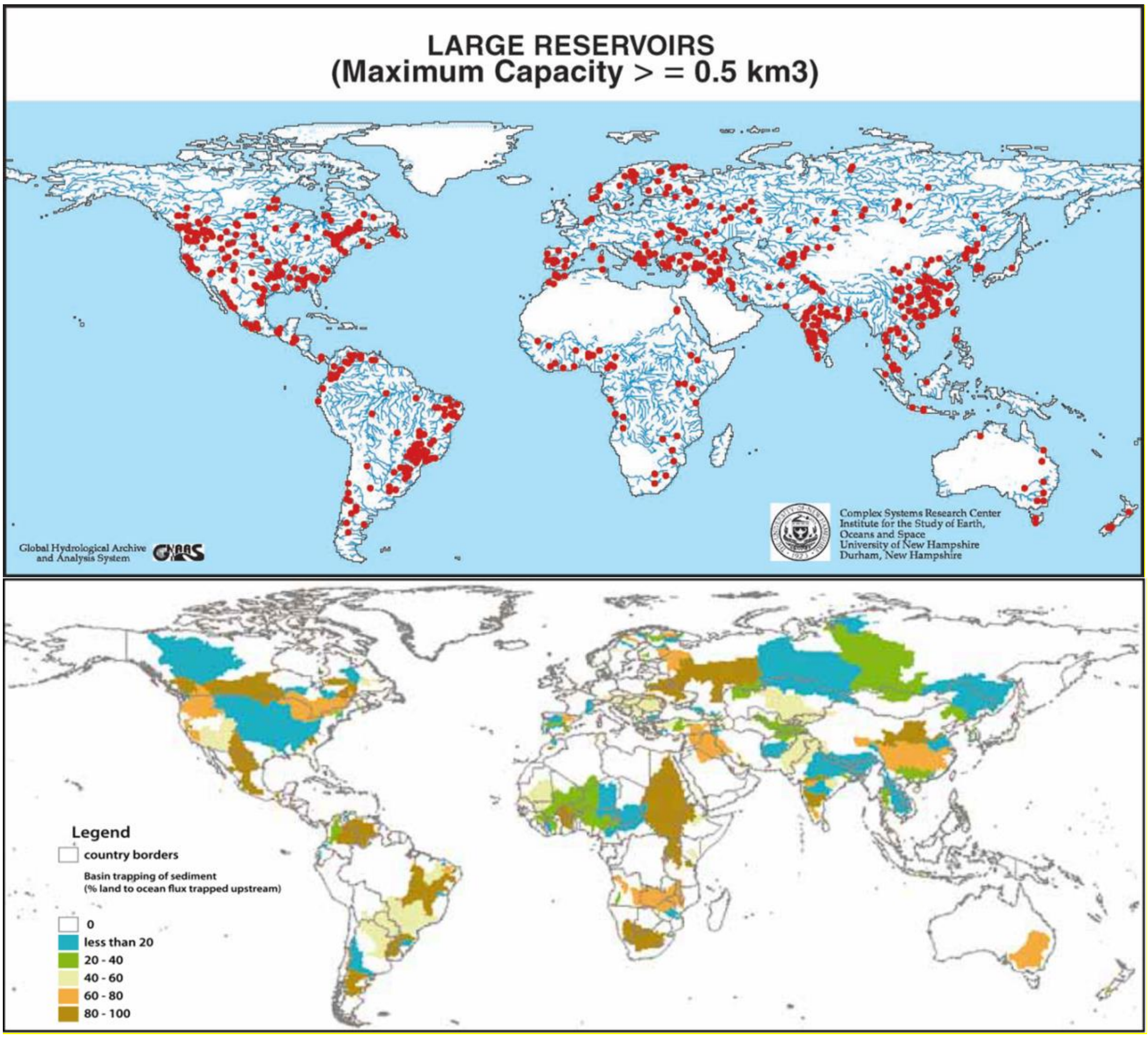

Figure 1. Overview of large reservoirs in 2003 and associated basin trapping of sediment (Vörösmarty et al., 2003).

Growing population in deltaic regions demands for room for living, industry and healthy environment, with increased need for sustainable nature-based land reclamation and coastal protection. These developments demands for sediment as building material, especially sand. Large river delta regions are however often characterized by fine sediment deposits (mud), which are not typically considered as a construction material, certainly not on a large scale.

2 LIVING LAB FOR MUD: A INTEGRATED SEDIMENT MANAGEMENT APPROACH BASED ON BUILDING WITH NATURE

With these societal challenges and needs in mind, EcoShape, a non-for profit BwN-based knowledge development consortium, initiated the Living Lab for Mud (LLM). The LLM is an initiative that aims to develop *integrated* knowledge and technologies to improve understanding and implementation of management, use and reuse of fine and soft sediments, based on the *BwN approach*. Through pilot projects, the LLM integrates the physical processes of sediment management, ecological and biological aspects, and the socioeconomic and governance perspective. The physical processes of sediment management focus on fine and soft sediments (mud) covering the entire physical liquid to soil spectrum: from sedimentation and resuspension, to transport and fate, to consolidation and strength development. The LLM is based on the BwN approach. This means making the best use of the natural dynamics (e.g. currents, waves, sediment fluxes, vegetation patterns) typical of specific deltaic ecosystems, to optimize soft sediments management and (re-)use (De Vriend et al. 2015). The LLM therefore fits with the BwN paradigm shift of thinking, acting and interacting *with* instead of *against* nature when designing hydraulic infrastructure solutions (De Vriend and Van Koningsveld, 2012).

To achieve successful implementation of integrated BwN solutions significant development of system understanding and process knowledge is necessary on the complete chain of sediment management, its link with ecology and biota, and (region-specific) socio-economic aspects. For example, while the insights in the mechanisms behind landscape formation in (natural) muddy systems by biogeomorphological interactions have substantially grown in the last decade (Borsje et al., 2011), the ability to reliably and sustainably design and build with mud is limited. Similarly, rigorous quantification of cost-benefit analysis and a legal and contractual framework that regulates BwN solutions implementation and management are lacking.

In line with the EcoShape BwN research program, the LLM combines fundamental research with pilot application. The pilots take place on smaller and larger scales, in the moderate climate of the Netherlands and in tropical climates elsewhere. At this moment, a number of pilot projects are included in the LLM initiative. EcoShape intends to further expand this portfolio with other pilots in the Netherlands and abroad. In the following section of this paper three pilots are presented in details, selected to include two Dutch and one Indonesia applications and to cover the broad LLM spectrum from mud transport to transition to soil.

3 THE LIVING LAB FOR MUD PILOTS

3.1 Salt marsh development by a Mud Motor, Harlingen, The Netherlands

In the Port of Harlingen, the yearly maintenance dredging requirement to safeguard navigation is about 1.3 million m^3 of mainly fine sediments. This material is conventionally disposed in the Wadden Sea, at two designated disposal locations that are relatively close to the port entrance. A considerable amount of this sediment is transported back towards the port, by natural hydrodynamics such as tidal currents and waves, leading to a cyclic series of dredging and disposal. This is not only economically inefficient, it may also lead to increased local turbidity, with a negative impact on primary production and ecological food chains (Reise 2005, Lotze et al. 2006, Eriksson et al. 2010, Elias et al. 2012).

In the LLM Mud Motor pilot a considerable part of the dredged sediment is disposed at a different location (see Figure 2) located in shallow water further away from the port. The local hydrodynamics are expected to pick up the sediment and naturally transport it towards the nearby salt marsh by the flood-dominated currents. This generates several positive effects:

1. Reduce recirculation towards the harbour, hence less maintenance dredging;
2. Promote the growth and stability of salt marshes, improving the Wadden Sea ecosystem;
3. Stabilize the foreshore of the dykes, which leads to lower maintenance cost of the dyke.

The research program that is set up around this pilot project strives to determine the effectiveness of this approach. Firstly, the necessary licenses to work within the protected nature area had to be requested (Baptist 2015). Next, the new disposal location for the Mud Motor was determined based on numerical model predictions, tidal predictions and technical feasibility (Grasmeijer 2016). The effectiveness of the Mud Motor in accreting the foreshore was determined through the use of tracers. Two types of tracers were released at the existing disposal location in front of Harlingen, and at the new disposal location respectively. The retrieval of the tracers in the study area determines the effectiveness of dredged sediments reaching the salt marsh area. The results indicated that 80% of the mud disposed at the Mud Motor location reaches the intertidal area where salt marsh enhancement is desired, compared to only 20% from the existing location (Vroom et al. 2016).

From September 2016 to April 2017 the first phase of the pilot project was executed. In total 300 000 m^3 of sediment was disposed at the new location using a small hopper dredger with a volume of 600 m^3. Sediment is only disposed during the flood tide when the current direction is towards the salt marsh. It is hypothesized that the increased sediment load of the tidal flows over the salt marsh will increase due to the Mud Motor, thereby increasing accretion rates of this marsh. The salt marsh accretion is measured with Sedimentation-Erosion Bars and LiDAR. Salt marsh accretion is the result of the balance between sediment deposition, sediment erosion and soil compaction. Preliminary results showed that close to 10 cm of sediment accreted on the salt marsh in the first two months of the pilot experiment, which is a rather high deposition rate. However, in later months, the accreted sediment eroded away indicating a lack of stabilising conditions. A natural stabilising factor for accreted sediment is the development of perennial vegetation on the salt marsh. Perennial vegetation lowers the hydrodynamic energy from currents and waves, thereby increasing the sedimentation rates on the marsh. The root systems stabilize the soil which reduces the potential for erosion. As a result a vegetated saltmarsh is likely to continue to accumulate sediment. Perennial vegetation on a salt marsh can develop at a height of at least mean high water (MHW). The mudflat and saltmarsh accretion, therefore, needs to be large enough to develop to this morphological height. Once perennial vegetation establishes, it will stimulate accretion by positive feedback processes. The development and cover of perennial vegetation is monitored with photography from an Unmanned Aerial Vehicle and with in situ measurements of vegetation density.

The pilot experiment continues in September 2017 with additional disposals at the new site and monitoring will continue as well. Within the Mud Motor pilot project in Harlingen, the natural salt marsh system is being fed with a local surplus of fine sediment deposits. Meanwhile the salt marsh accumulates and stabilises sediment, which creates values in the form of coastal protection and turbidity reduction within the system. Integrating sediment dynamics and ecological services, the Mud Motor can be a typical catalyst of the development of this system and the project therefore delivers a valuable contribution to the goals of the LLM program.

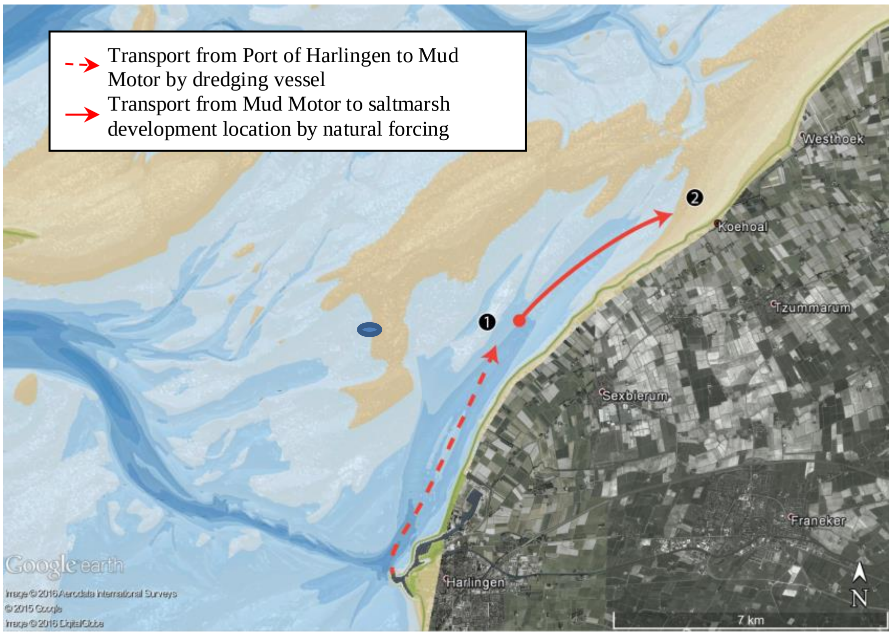

Figure 2. Overview of dredge site (Port of Harlingen), (1) Mud Motor location and (2) salt marsh of Koehoal

3.2 Securing eroding delta coastlines, Demak, Java, Indonesia

In the tropics alluvial coasts are often muddy and covered with mangrove forests. In Demak, a stretch of 20 km of coastline along the north coast of Java is facing severe erosion problems. These are mainly due to groundwater extraction -which causes land subsidence- and the removal of natural mangrove forests to build extensive aquaculture. The conventional response to the eroding processes is the implementation of hard hydraulic structures, such as concrete seawalls. Besides this being a relative expensive solution in a region like Demak, the physical boundary condition for these types of structures is unsuitable: the soft seabed provides insufficient stability for these large structures resulting in collapse over time. Furthermore, the rigid structure blocks the sediment laden flows and reflects the incoming waves rather than damping them. Reflected waves initiate scour along the foot of the structure resulting in instability (Van Wesenbeeck et al, 2015). In 2015, a large-scale BwN pilot was initiated, aiming to provide coastal security and supporting the revitalization of at least 6,000 ha of aquaculture ponds along a 20 km shoreline in the Demak district (Central Java), thereby enhancing the resilience of 70,000 vulnerable inhabitants of the area. This is accomplished through the implementation of both social and physical coastal safety measures.

Coastal field schools are set up to train local community groups in sustainable aquaculture practices, alternative livelihoods and sustainable restoration and maintenance of the mangrove green belt. Best aquaculture practices have boosted productivity and income of farmers, inspiring farmers to replicate the approach in 100 ha own ponds. In addition, community groups will receive continued (financial) support to further enhance sustainable aquaculture and livelihood practices while engaging in the restoration of mangroves through the so-called biorights mechanism.

Rather than implementing ineffective hard structures to provide coastal safety, a low tech engineering solution was developed to restore the severely deteriorated mangrove green belt (Figure 3). Permeable dams made of bamboo and brushwood were constructed in front of the existing coastline, within the intertidal zone. The permeable dams reduce the wave energy and provide sheltered areas where the sediment loaded waters can deposit the fine sediments. Layer by layer, the grid cells behind the permeable dams are filled up. Once sufficiently filled, mangrove seeds can settle in the freshly deposited sediment layer, slowly restoring the mangrove green belt with no need for planting mangroves. When a sheltered area has filled up with sediment and mangroves are sufficiently regrown, a new permeable structure is built seawards of the previous one to gradually extend the shore zone seawards from the coast. Once the mangrove greenbelt is restored, the mangroves can once again attenuate the waves and build up sediments to counterbalance subsidence and sea level rise to a certain extent.

Since the start of the project, a total of 2600 m of dams have been constructed by the project together with the Indonesian government (Figure 4). The Indonesian government is replicating the approach across Java, investing 1.5 million EUR in 2016, and joint guidelines are being developed to share lessons learned and best practices. Two years after the construction of the first dams, monitoring results show a net sedimentation of 30 centimetres at some locations behind the dams, whereas control sites show a net erosion of 5 cm. Monitoring results show that the concept clearly works, however, recent observations indicate that subsidence might be more severe than previously anticipated. To halt subsidence as a result of ground water extraction, effective integrated water resource management on a landscape scale, including the city, is to be implemented to stimulate use of alternative fresh water sources.

Although the pilot project is only half way, initial results show that by making use of relatively low tech solutions, restoration of a degraded muddy coasts is feasible. Furthermore, this pilot shows that social awareness is of utmost importance for sustainable coastal zone management and that communities and governments can be successfully mobilised. These insights contribute in delivering tools and building blocks to the overarching vision of the LLM development.

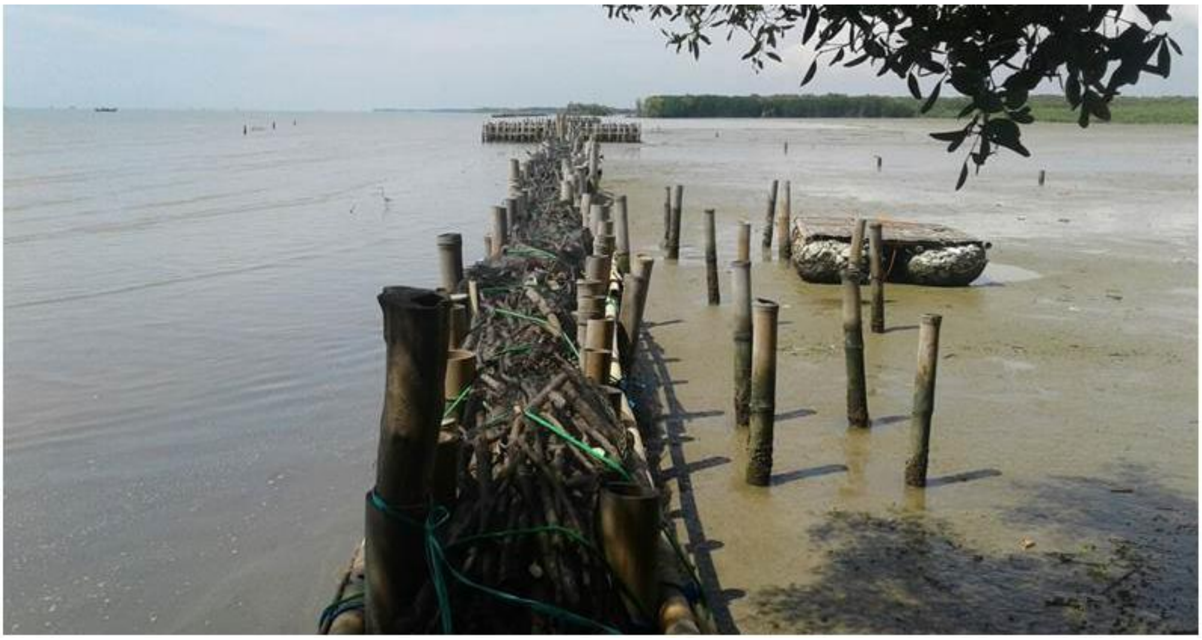

Figure 3. Sedimentation behind permeable dam constructions

Figure 4. Aerial view of permeable dams at the pilot project location

3.3 Ripening mud to clay, Delfzijl, The Netherlands

The Port of Delfzijl is located in the Ems River estuary near its confluence with the Wadden Sea and the North Sea. Since a few decades the turbidity caused by the Ems River has been increasing due to increase in suspended sediments concentration (van Maren et al. 2015), leading to an increase in required maintenance dredging for the harbours in the Ems Estuary, such as Delfzijl. At the same time, the clay needed to maintain or strengthen the dikes in the area is bought and brought in from distant locations. Therefore, instead of disposing the abundant fine sediments dredged from the Delfzijl harbour in open water, transporting it and letting it ripen on land offers a potential opportunity to generate clay for the nearby dikes. At the same time this contributes to decreasing the turbidity of the Ems river and improving water quality. This presents an attractive win-win situation which takes advantage of BwN processes such as evaporation and consolidation, to turn sediment into clay soil. Also it creates and opportunity for reuse of dredged sediments which are commonly considered unsuitable and permanently disposed offshore. This would in turn result in decrease of dredging works.

With this opportunity in mind, EcoShape cooperates with the Province of Groningen, the waterboard 'Hunze en Aa's', the Delfzijl harbour developer Groningen Seaports, nature organisation Groninger Landschap and the Dutch ministry of Infrastructure and Environment to initiate the 'Pilot Kleirijperij' with co-funding of the Waddenfonds, which consists of dredging mostly fine sediments from the Delfzijl harbour and nature area Polder Breebaart, hydraulically transport it on land and deposit it in a series of tests cells. Here the sediment is ripening for about 4 years until this clay soil is ready to be utilized for dike reinforcement (Figure 5). The pilot includes 24 test cells, covering an area of about 22 ha and a varying depth with a maximum of 1.5 m. Various deposition and ripening strategies will be tested in the cells such as different deposition layer thickness, dry or wet consolidation, seeding vegetation or enhancing ripening by mechanical tools. During ripening, the cells will be monitored to test consolidation and desalination rates. Deposition in the cells is expected to start in spring 2018.

The ultimate objective of this pilot is to test different ripening strategies with respect to efficiency in ripening and in delivering quality clay. At its termination in 2021, the pilot will have to deliver 70,000 m^3 of clay for use in a demonstration project of the green dike concept 'Brede Groene Dijk'.

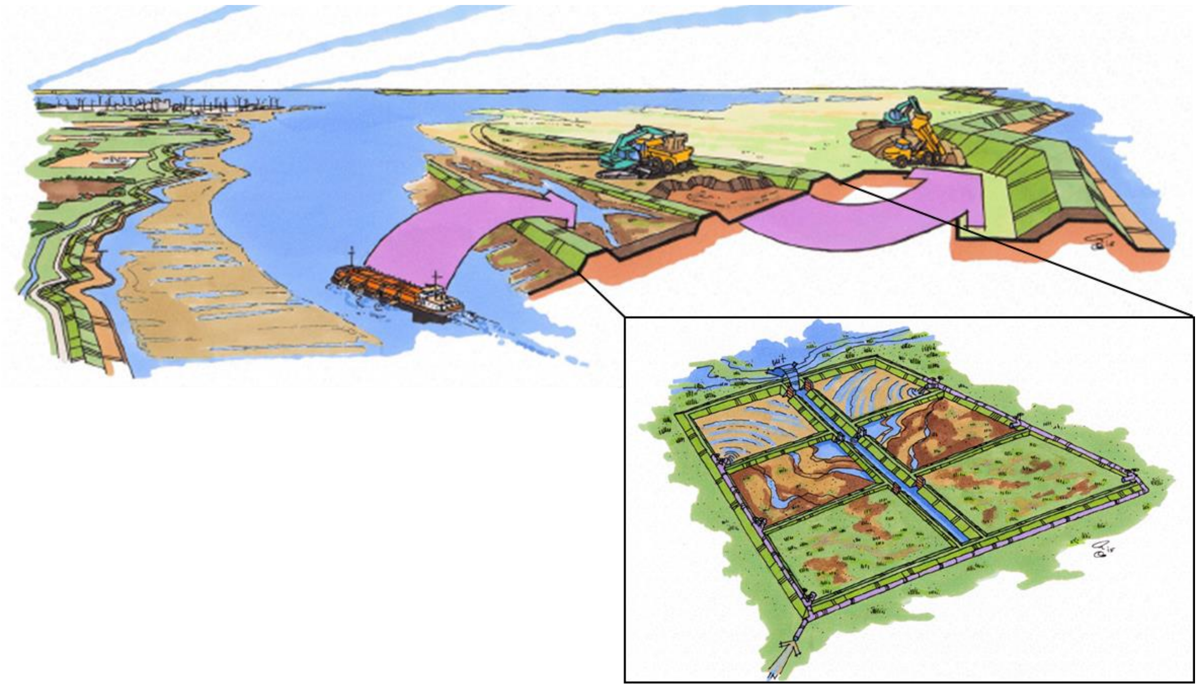

Figure 5. Artist impression of the Pilot Kleirijperij concept

4 CONCLUSION

Integrate, with nature, beneficial use of fine, soft sediments (mud) is critical to fulfil societal needs. To establish beneficial use in the common engineering practice it is necessary to develop and share knowledge and innovative construction practices using integrated, BwN-based solutions, and to demonstrate feasibility in pilot projects. EcoShape initiated the LLM to achieve these objectives. The current pilot projects will produce results within a specific combination of natural systems, societal needs and Regional context (estuarine and port maintenance, mangrove and coastal rehabilitation, fresh water lake and ecosystem restoration, The Netherlands and Indonesia). In order to fulfil the full potential of a Living Lab dedicated to Mud, more pilot projects are needed (for example on ripening in tropical conditions) connected under the LLM. EcoShape is open to discuss potential pilots with parties interested in this concept and to share the knowledge from the pilots already initiated.

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