Use of dredged sediments as a sustainable material

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1 Abstract

Sediment is dredged from the bottom of rivers and harbours to keep inland shipping and marine traffic possible. All over the world hundreds of millions of cubic meters of sediment is dredged annually. Human activity surrounding those rivers and harbours are a source of pollutants that are ingrained in the sediment. A huge part of the dredged sediment is classified as waste and is dumped in sea or on land. There are however many valuable resources present in sediments that now go to waste. Dredged sediments consist predominantly of eroded rock and soil in the form of sand, silt and clay. Those are non-renewable resources used in applications ranging from building materials to plant growing media. Organic matter and heavy metals present in dredged sediments can be used for beneficial purposes. This review paper aims to address why dredged sediment is not completely used as a resource and whether these barriers can be overcome. There are several reasons why not all dredged sediment is used. These include the inconsistent composition of the dredged sediment, the common occurrence of pollutants in sediment and the high cost associated with using dredged sediment compared to other sources. Construction materials are held to high standards, as buildings and roads should be safe. The variable nature of dredged sediment causes construction materials made from them to have different attributes. High costs also are a barrier in the use of dredged sediments. Steps needed to prepare dredged sediments for use results in higher prices compared to similar resources. These barriers lead to a low demand for dredged sediments. Cost would go down with increased use of dredged sediments, as processes will become more efficient and new methods of cleaning will be tried. Regulations from the government could help streamline this process, by standardising test for sediment compositions and lifting the ‘waste’ classification of dredged sediments.

2 Layman's summary

Rivers and harbours are an essential part of our infrastructure. Boats sailing through them need the water to be deep enough that they don't get stuck. However, small parts of rock and soil flow down the river and settle on the bottom. The collection of particles on the bottom of rivers is called sediment. Over time the build-up of sediment lowers the depth of the rivers and harbours. Port and river authorities remove the sediment periodically to make sure boats can reach their destination. This process of removing sediment is called dredging. Millions of cubic meters of sediment get dredged annually around the world. A big part of this is considered waste and is put in a landfill or dumped on sea. Dredged sediment could however be used as a resource for various applications, lowering the need for resources from non-sustainable origins. Dredged sediment could for example replace sand in the production of concrete and to make building bricks. So why is a big part of dredged sediment not used for these beneficial purposes and considered a waste?

A lot of other substances gather in de sediment next to the eroded rocks and soil. These include organic matter from decaying plants and animals, salt and other minerals as well as harmful contaminants from industry and transport. Concrete will get weaker when a lot of organic matter is put into it, as do some minerals found in dredged sediments. The harmful contaminants could leak out into the environment where the contaminated sediments are used. This means that the other substances have to be extracted from the dredged sediment, which can be an expensive process. A part of the harmful contaminants are heavy metals. These are toxic to plants and animals, however we use them abundantly in our technologies. Heavy metals extracted from the sediment can be sold and result in a clean sediment that can be used as a building material.

The extraction of dredged sediment is an expensive process. Resources from other origins are often cheaper, which makes them preferred. Using dredged sediments is however a more sustainable option, as these are already available and don't have to be extracted from a quarry. More research into new processing techniques for dredged sediment should decrease the cost. Government legislation about the use of dredged sediment could also stop this potential resource go to waste. Together, this literature review gives an overview of why dredged sediment is not completely used as a resource and whether these barriers can be overcome.

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3 Introduction

Sediments are the result from naturally occurring deposition of sand, silt, clay, organic material and other components in water bodies. Sand, silt and clay particles are the result of erosion of rocks and soil upstream of the deposition. Once water flow slows down, the suspended sediment gets deposited. Sediments are an important part of aquatic ecosystems as they provide habitat for plants and animals (Erftemeijer & Robin Lewis, 2006). On the other hand, the build-up of sediment hinders the passage of boats and decreases the amount of water that a water reservoir can store.

Regular dredging is needed to maintain water traffic and keep water reservoirs from filling up. Dredging is also used to keep harbours open and to construct new waterways. This results in millions of cubic meters of dredged sediments in Europe alone (Beddaa et al., 2020). Dredged sediments are often seen as a waste stream, resulting in its disposal in the deep sea or in landfills (Beddaa et al., 2020). Disposal in the deep sea has come under scrutiny in the last decade because of concerns about the disturbance of habitat and the overall marine environment (Dauji, 2017; Essink, 1999). In contrast, disposal of dredged sediments on land is often not a problem if the sediment is local and has the same chemical properties as the land surface it is distributed on. However, when the salinity of the dredged sediment is higher than is allowed or when there are other contaminants present, the dredged sediments have to be deposited in landfills (Bates et al., 2015). However, landfills are expensive due to scarcity of non-occupied land around the world and the precautions needed to contain potential contaminants from leaking to the local environment (Bates et al., 2015).

Dredged sediments do not have to be a waste stream. Beneficial uses of dredged include beach nourishment, structural shoreline protection and heightening of land. Moreover, the sand that is part of the natural composition of sediments can be used in concrete for construction (Amar et al., 2021). As the world tries to be more sustainable by using less resources, an alternative source of sand could lower the need to harvest virgin resources. Recycling dredged sediment helps moving to a circular economy. The usability of dredged sediments depends on composition and possible contaminants (Bhairappanavar et al., 2021). For instance, the amount of organic matter influences the processing that is needed before the use in concrete. Contaminated sediments do have potential uses. For instance, heavy metals can be retrieved from it (Norén et al., 2020).

Despite the various uses, a high percentage of the yearly dredged sediments is considered a waste (Mymrin et al., 2017). This review paper aims to address why dredged sediment is not completely used as a resource and whether these barriers can be overcome.

4 Methodology

To perform the analysis of this study an extensive literature search on Google Scholar and Web of Science was carried out with combinations of the following keywords: dredged sediments, dredged marine sediments, dredged sludge, dredging, marine dredging, river dredging, sustainability, sustainable, CO2 emissions, pollution, greenhouse gas emissions, waste recycling, natural resources. The focus of this review paper is on papers published in 2017-2022. For papers on detailed processes or example cases, papers published in the last 20 years were examined because of the limited number of publications in the last 5 years.

5 Sediment compositions

To understand the potential value of dredged sediment it is important to know what it is made of. Sediment composition depends on the origin of the sediment. The bulk of sediment consist of water and small particles of eroded rock, soil and minerals. The fine particles of eroded rock and soil are categorised in silt, clay, sand and small rocks depending on the particle size (Ferrans et al., 2021). This article focusses on sand and smaller particles, as rocks are easily sieved out of the dredged sediment and have multiple uses. The grain size of sand has a diameter between 2 mm and 0.062 mm, silt between 0.062 mm and 0.002 mm, and clay has a particle diameter of less than 0.002 mm (Burdige, 2006). Usually, the sediment consist of a mixture of particles of different diameters (Figure 1A). The more a soil has eroded over time the smaller the average particle diameter will be (Mymrin et al., 2017).

The chemical composition of sand, silt and clay varies depending on the type of rocks it originates from. The most common constituent is silica (SiO_2), which is frequently found in the form of quartz. Quartz is the second most common mineral on earth and is found among other in granite, sandstone and shale (Burdige, 2006). Silica usually makes up 40-80% of the bulk of dredged sediments (Bose & Dhar, 2022). Next to silica various other natural minerals are found frequently in sand, silt and clay. Depending on the origin of the sediment, aluminium oxide (Al_2O_3), calcium oxide (CaO), magnesium oxide (MgO) and iron oxide (Fe_2O_3) each make up 0,5-20% of the dredged sediments (Bose & Dhar, 2022).

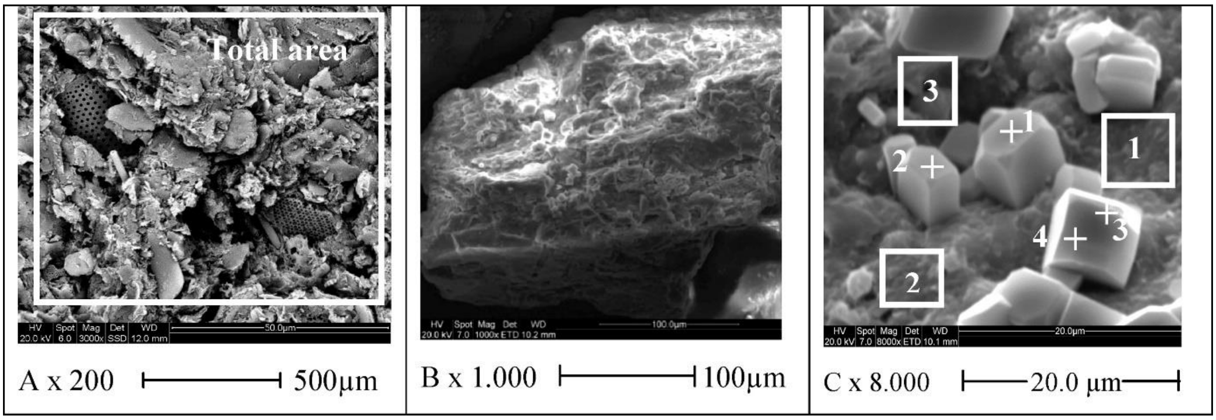

Figure 1 Electron microscopy images of dredged sediment from the harbour of Paranaguá, Paraná state, Brazil. (A) The different sizes and structures of various particles. (B) The shape of a grain of sand. (C) The hex-octahedron salt crystals on a grain of sand. (Mymrin et al., 2017)

The ratio between sand, silt and clay depends on the material it eroded from and the time it had to erode into smaller particles. The particle size will be larger when a waterway is repeatedly dredged (Mymrin et al., 2017). Analysing the dredged sediment over time will be important to keep an insight into what the particular ratio is in question is. Dredged sediment contains various other components next to eroded rock and soil. These components very according to the origin of the dredged sediment. The first of these components is organic matter. This can be parts of decaying animals and plants as well as living plant roots and small animals that have burrowed in the top layer of the sediment. The other components found in dredged sediment, like organic matter, will predominantly accumulate in silt and clay fractions, because their particle size is also usually smaller than 0.062 mm (Beddaa et al., 2020). The bigger grain size of sand causes that most other particles wash out of this fraction of the sediment when sieved (Ferrans et al., 2019).

The second group of components consist of non-hazardous chemicals and nutrients like nitrogen and salts (Figure 1C). Nitrogen found in dredged sediment is predominantly nitrate (Kiani et al., 2021). These components could interfere with beneficial use when they are present in high concentrations (Ferrans et al., 2019).

The third group consists of organic compounds that remain in the soil for extended periods of time. This group consist of aromatic compounds, polycyclic aromatic hydrocarbons (PAH) and polychlorinated biphenyls (PCB) (Ferrans et al., 2021) and include benzene, toluene, ethylbenzene and xylene. PAHs can originate from natural sources as well as from human activities (Vane et al., 2014). PCBs do not occur naturally in soil and are always the result of human activity. PAHs and PCBs have a long half-life, ranging from years to decades, which means they stay in the soil for long periods of time. Organic compounds, PAHs and PCBs have been shown to negatively affect environmental and human health (Vane et al., 2014).

Finally, the fourth group of components regularly found in dredged sediments are heavy metals. Heavy metals are just like organic compounds considered a contaminant because they have adverse effects on environmental and human health. Heavy metals that are usually detected in dredged sediments are arsenic, lead, cadmium, copper, chromium, nickel and zinc (Ferrans et al., 2021). These metals are found in different chemical compositions, ranging from part of a mineralogical structure to being part of a salt structure (Hashim et al., 2018). Naturally these metals occur in sediments in low concentrations. However, industry in ports and the burning of fossil fuels on ships, among other sources, cause the level to increase to toxic concentrations.

To summarise this chapter, dredged sediments are a mixture of particles precipitated from the water. Rivers bring eroded rocks, soils and minerals in various sizes, which form the bulk of the sediment. Various metals, organic matter and other compounds are deposited to the bottom of the rivers and collected in the sediment. The exact mixture of all these components depends on what type of rocks, soils and human activity is found along the supplying river. To assess the potential value of dredged sediment it is important to know what it is made of.

6 Beneficial uses of dredged sediment being used on large scale

Not all dredged sediment is disposed as waste. This chapter describes the large-scale applications of dredged sediment. Dredged sediment from rivers and small streams is being used on the land adjacent to it to increase the height of the land where the top soil has eroded (Lieten & Zuijdam, 2020). This beneficial use has the additional benefit that the emission and cost of transport are close to zero. The organic matter in the sediment can be beneficial for the farmland it is deposited on.

Dredged sediment from ocean harbours is used to strengthen coastal defences and to expand beaches (Gailani et al., 2019). In a project at the coast of the Netherlands dredged sediment is used to enhance a salt marsh outside the dikes near Harlingen (Baptist et al., 2019). Dredged sediment from the port of Harlingen is disposed at flood tide downstream of the salt marsh. The currents allow a natural deposition enhancing the natural landscape (Figure 2). Using currents to deposit dredged sediment is called the Mud Motor technique. For a mud motor to work it is important that the depositing site has a strong current. The current has to slow down at the intended site for disposition for the dredged material to precipitate. Mud motors are used in various forms around the world (Gailani et al., 2019).

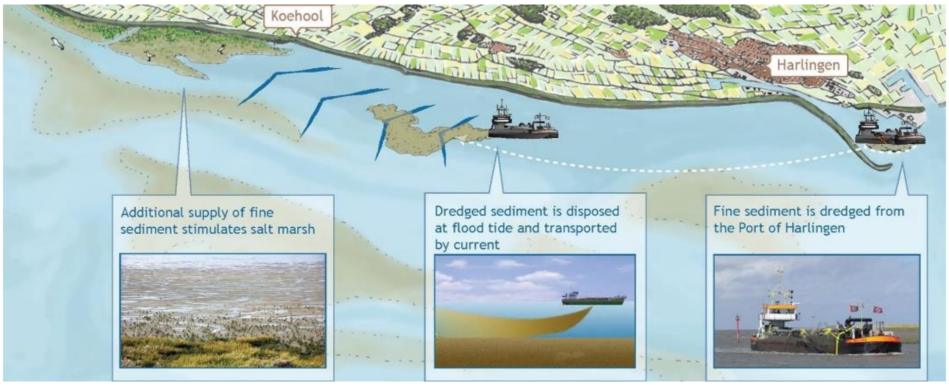

Figure 2 Schematic overview of the Mud Motor project near Harlingen, the Netherlands. Dredged sediment from the port of Harlingen is deposed downstream of the salt marsh to enhance this biome. (Baptist et al., 2019)

Another use of dredged sediment is to cap solid waste landfills (Welch et al., 2016). The capping of these landfills prevents gasses to escape the landfill. Dredged sediments are used in a similar fashion to fill former strip mines. The choice for dredged sediment over soils and construction waste is the cheaper price (Welch et al., 2016). Dredged sediment is also used in the construction of small dikes to act as buffers between a community and adjacent land uses like an industrial complex (Piesschaert et al., 2005).

To conclude, dredged sediment is currently used for large scale applications. Including the use to increase the height of land, to create natural habitats, to cap landfills and to increase shore protection. These uses require no processing of the sediment. No analysis has been done about how much sediment is exactly used for beneficial purposes compared to how much ends up as waste.

7 Potential uses of dredged sediments

Dredged sediments has a great deal more to offer than being used as a filler for landfills. The fine granular particles of broken rock are useful in several building processes. Other components like organic matter and heavy metal contamination also have their own applications.

7.1 Building materials from dredged sediment

Experiments to use dredged sediment in building materials have been done over the last decades, as 40 billion tons of granular material is used per year in the construction sector worldwide (Amar et al., 2021). In western Europe, the US and China alone around a billion tons of sediment are dredged each year (Amar et al., 2021). Sand, which is used to produce concrete, is a non-renewable resource that is harvested on land all around the world and is becoming scarce (Dhondy et al., 2019). The combination of all types of eroded rocks used in the production of concrete is called aggregate. Aggregate is also used as embankment material and in asphalt. The use of aggregate depends on the grain size of the material and the shape of particles. Sand that has eroded by wind, for example desert sand, doesn't adhere well to other particles, because it is too smoothly rounded (Liu et al., 2020). Sand eroded by water is more jagged, so it adheres better to other particles (Beddaa et al., 2020). Because of this, concrete is made from aggregate recovered from rivers and flood plains.

Dredged sediment has several drawbacks compared to commonly used sand that impair the quality of the end product, whether that is concrete, an embankment or another application. These drawbacks are the high amount of organic matter (5-30%), high water content, small particle size and common occurrence of contaminants (see Chapter 5) (Amar et al., 2021). However, there are methods to improve the mechanical properties of dredged sediment for each of these drawbacks. Organic matter can be separated by sieving, or burned away by heating the sediment in an oven to

800-1200 °C (Beddaa et al., 2020; Crocetti et al., 2022). Organic compounds like aromatics, PAHs and PCBs will break down at these high temperatures. High water content can be lowered by letting the sediment settle in a containment site and then removing the top layer of water. Alternatively, the dredged sediment can be sieved or heated, although this is an energy consuming and cost intensive process (Crocetti et al., 2022). The average small particle size of dredged sediment can be mediated by sieving (Beddaa et al., 2020). The segment with smaller particles could be used in other applications such as in the ceramic industry, while the segment with bigger particles can be used for building materials. When contaminants cannot be removed from the dredged sediment, they can be fixed in the sediment. The idea is that fixed contaminants cannot leach into the environment. Fixation can be done by a binding agent like cement. The strength, setting and shrinkage of concrete is affected when fine particles and organic matter are left in the aggregate. Concrete with acceptable strength levels can be made from dredged sediment when the sandy fragments are used (Beddaa et al., 2020).

Bricks can also be made from dredged sediment instead of using concrete or clay (Figure 33). Bhairappanavara et al. (2021) reported that using around 88% dredged sediment by weight mixed with 12% Portland cement creates eco-friendly bricks. They made a life cycle assessment for the bricks and compared it with conventional fired clay bricks and concrete masonry units. The life cycle assessment included extraction, transportation and manufacturing. Dredged sediment bricks have an embodied energy of 1.49 MJ/kg, compared to 4.88 MJ/kg and 2.32 MJ/kg for clay and cement bricks. The CO_2 emissions where 0.162 kg CO_2e/kg of dredged sediment bricks, compared to 0.558 kg CO_2e/kg and 0.410 kg CO_2e/kg for clay bricks and concrete masonry units. They concluded that their dredged sediment bricks require 2.5 to 3.4 less CO_2 equivalent emissions compared to the conventional bricks used in construction. The dredged sediment originates from the Cuyahoga River in Ohio. Around 172,000 m^3 sediment is dredged from that river each year that is available to make bricks from (Bhairappanavar et al., 2021).

Figure 3 Bricks made from dredged sediment made by the Dutch company Waterweg. These bricks are made from local dredged sediment and let rainwater pass through to alleviate sewer systems during rain showers. Source: Waterweg Rotterdam B.V.

In this chapter various applications of dredged sediment in construction materials are discussed. Aggregates found in dredged sediment are an eco-friendly alternative for quarried aggregates like sand. Aggregate from dredged sediment can be used in road construction, embankments, concrete and to make bricks. Aggregates from dredged sediment require more binding agents like cement compared to aggregate from other sources, due to the average small particle size. However, the transport of quarried aggregate usually has a higher emissions impact than transport of dredged sediment, due to longer distances (Crocetti et al., 2022). Using dredged sediment over quarried aggregate should have lower climate impact when used close to the source.

7.2 Heavy metal extraction

Sediment is the collection place of everything that precipitates from the water. Heavy metals are often found in sediment as discussed in Chapter 5. Most often this is only a naturally occurring trace element of these metals. However, the concentration of heavy metals has increased in many rivers and harbours due to human activities (Hashim et al., 2018). These metals are found in different chemical compositions, ranging from part of a mineralogical structure to being part of a salt structure. Heavy metals that are part of a mineralogical structure are unlikely to be bioavailable, due to strong bonds to aluminosilicate minerals. Heavy metals that are in a salt formation or have other weak chemical bonds are more easily bioavailable and could be toxic for a marine ecosystem as well as for life on land (Ferrans et al., 2021). There are several options for handling these polluted sediments, like fixing the dredged sediment or putting it in a landfill. Nóren et al. (2020) estimates that sending contaminated sediments to a landfill cost between $120 and $1350 per tonne, while they estimate that metal recovery cost between $100 and $250 per tonne. The saving on landfill cost alone could make the following metal recovery strategies economically viable.

There are three groups of strategies to extract heavy metals from the dredged sediment. None of these processes is currently being used at a large scale due to lack of research and regulatory incentives (Ferrans et al., 2021). The first extraction strategy is electro-chemical separation. The heavy metals have to be soluble ions for this method, or be bound to oxides, hydroxides or carbonates (Akcil et al., 2015). An electric current along an anode and a cathode moves the metals to the anode. The metals that accumulate around the electrodes have to be washed off and collected (Kirkelund et al., 2009). With this method up to 98% of heavy metals was removed after 14 days (Kirkelund et al., 2009).

The second strategy is washing the heavy metals out of the sediment (Pal & Hogland, 2022). This is done by first making the pollutants soluble with acids or other chemicals. The chemicals can then be physically washed from the sediments by water jets, followed by treating the water to let the metals precipitate from the water and be collected. Various other contaminants, like salts, are also washed out of the sediment due to the nature of the chemicals. These have to be later separated from the chemicals. The physical washing from contaminants works best on sediments with bigger particle sizes, which eliminates the dredged sediment with higher concentration of finer particles (Akcil et al., 2015). The usage of acids and other chemicals to make the metals soluble also has a negative impact on the environment. However, this depends heavily on the method used. A toxic solvent like EDTA will persist in the environment for a long time, while a naturally produced compound like citric acid will be broken down more quickly. On the other hand, EDTA removes up to 86% of the heavy metals out of dredged sediment, while citric acid has an efficiency of about 50% (Akcil et al., 2015). Calculating the exact environmental impact of each metal involves the production and ecological impact of the solvent, energy use of the process and the efficiency of removing the heavy metals. Heavy metals left in the dredged sediment could have a negative environmental impact when leaching into the environment (Akcil et al., 2015).

The last of the three strategies involves bioaccumulation by microorganisms. Several experiments have been done with bacterial and fungal communities (Akcil et al., 2015). These processes are a lot slower than the washing out of heavy metals, taking up to 60 days instead of only several hours (Cecchi et al., 2019). Cecchi et al. (2019) used a method in which fungi would first colonize a membrane for a week. Then the membrane is inserted into dredged sediment for up to 60 days. This allows the fungi colonies on the membrane to bioaccumulate the heavy metals. The fungi in this experiment were best at accumulating Cu and Zn, with the Cu and Zn having a relative concentration on the membrane of 75% and 207% after 60 days compared to the original Cu and Zn concentration in the sediment. In this experiment they used *Penicillium expansum* Link *and Paecilomyces formosus* based on the local communities. Using a different combination of microbes could lead to absorption of a wider range of heavy metals. Using bioaccumulation is not by definition environmentally better than a strategy like sediment washing. Beolchini et al. (2013) reported that using citric acid washing has a 8 times lower CO_2 emissions equivalent compared to a use of bioaccumulation with bacterial strains, mostly due to the high energy consumption of the bioaccumulation process.

This chapter covered the extracting of heavy metals from dredged sediment. Sediments downstream from centres of human activity have been contaminated with heavy metals. Contaminated sediments cannot be used without care because the possible leakage of contaminants to the environment. Strategies to exact the metal vary in cost, time investment and sustainability. No studies currently have a complete overview of all cost and environmental impacts. However, Europe alone is able to produce up to 100 million m^3 of contaminated sediments, of which many are contaminated with heavy metals (Akcil et al., 2015). How much of these sediments are contaminated with heavy metals and how much of those metals can be extracted is not yet known.

7.3 Biogas

The organic matter in dredged sediment is considered a contamination when used in concrete and bricks as it weakens the structure (Beddaa et al., 2020). However, gas production from this organic matter could change it from a hindrance to a resource. Gebert et al., (2019) noted that structures made from dredged sediment and landfills where contaminated sediment is stored have noticeable gas production. Organic carbon in these deposits of dredged sediment is anaerobically degraded by microbes, mainly into methane gas (CH_4).

How much methane is produced from dredged sediment is not well documented. Dredged sediments commonly contains between 5% and 30% organic matter by weight (Amar et al., 2021). A recent case study by Martine et al (2021) tried to determine the gas emissions during the ripening of dredged river sediment intendent for dike reinforcements. They measured the CH_4 emissions over 3 months while the dredged sediment was drying in a reservoir (picture 4). They found some evidence of increased CH_4 emissions but could determine with certainty the scale of CH_4 emissions to the atmosphere. However, the study also included salty sediment, which had a significant lower CH_4 emission. The salty sediment had a similar percentage of organic matter at the start of the experiment and showed a similar degradation of organic matter. Gebert et al (2019) made a connection between the nitrogen concentration and CH_4 emission in their study. A higher nitrogen concentration directly correlates with the gas production potential of the dredged sediment. Nitrogen stimulates the growth of anaerobic microbes that produce the methane (Gebert et al., 2019). There was however no mention of nitrogen concentrations in the study by Marine et al (2021).

Figure 4 Sediment ripening. The first picture from the left shows an aerial view of the sediment ripening reservoirs. Sediment ripening over the duration of 3 months is shown in the other three pictures from left to right. Pictures from Martine et al. (2021)

Organic matter stays mostly in the silt or clay portions of the dredged sediment (Ferrans et al., 2019). Sieving out the clay and silt fractions can be used to lower the bulk amount of dredged sediment that has the potential of producing methane gas. Gas produced from dredged sediment can be collected in the same manner as gas produced by garbage disposals. Methane gas emissions from garbage disposals are regulated in Europe. Under the European Landfill Directive, landfill operator are obliged to reduce methane emissions to the air (Wang et al., 2020). The methane collected from landfills is used as biogas (Themelis & Ulloa, 2007).

Together, organic matter can take up to 30% of dredged sediment by weight, mainly present in the silk and clay fragments. This organic matter can be anaerobically concerted by bacteria into methane gas, which can be used as biogas in households or transport. A high nitrogen content in the dredged sediment is important for the anaerobic bacteria to grow.

7.4 Plant growing medium

Plants for food production and ornamental plants are grown on an industrial scale in plant growth media all over the world. These growth media usually consist of non-renewable materials like peat (Mattei et al., 2017). Peat extraction in particular has a high impact on the local environment and on greenhouse gas emissions. Dredged sediments could replace the use of non-renewable materials in plant growth media.

Mattei et al. (2017) conducted a case study in which they co-composted dredged river sediment with green waste from the local municipality. The dredged sediment first had to undergo some decontamination treatment to get rid of high PAH concentrations. The green waste consisted of pruning residues that would otherwise have limited uses. The resulting growth medium showed healthy microbial communities and showed no important eco-toxicity. Plants grown on the sediment-based medium showed similar growth patterns to plants grown on traditional growth media.

A similar case study by Kiani et al. (2021) used dredged sediment from a lake, which was enriched with nitrogen and phosphorus. The rye grass grown on different mixtures with this sediment grew well. They concluded that it was safe to use this dredged sediment in the direct surrounding to improve the local farmland without pollution the lake more.

Figure 5 Dredged growth medium experiment by Kiani et al. (2021) First picture shows rye grass grown on different combinations of sediment and soil. Bottom picture shows the root structure in the sediment after nine months.

Another study in Sweden used dredged sediment from a lake. Here the plants showed reduced growth due to nutrient deficiency and low availability of substrates (Ferrans et al., 2022). Growth can however be enhanced by mixing compost into the dredged sediment. The sediment from the lake was slightly contaminated with heavy metals. This resulted in high concentrations of cadmium in the lettuce grown, surpassing the maximum permissible concentrations. They note however that plants grown for bio energy or ornamental purposes could still be grown on this growth medium.

Dredged sediment has potential to act as a growth medium to replace non-renewable resources. Caution is however advised when dealing with contaminated sediments, as the resulting plants could surpass maximum permissible concentrations for consumption. Decontamination of the dredged sediment can be used when the growth medium is destined for agriculture.

8 Overview of the biggest barriers for large scale beneficial use of dredged sediment

In the previous chapters the current uses as well as potential new uses have been discussed. The potential uses of dredged sediments are plenty. However, a lot of sediment is still treated as waste. This chapter will give an overview of the biggest barriers for the large-scale beneficial use.

The composition of dredged sediment varies widely between points of origin, as discussed in Chapter 5. The exact composition of dredged sediment is important when dredged sediment is used for in construction. The particle size, the amount of organic matter and the concentration of minerals are all important for the strength and durability of concrete (Beddaa et al., 2020). Tests on the composition of the dredged sediment have to been done to ensure the safety of concrete constructions. However, there is no international standardised test to determine the quality of the dredged sediment and what the chemical composition is (Crocetti et al., 2022).

Contamination with toxic substances causes millions of cubic meters of dredged sediments to be destined for landfills (Barjoveanu et al., 2018). Cleaning the sediment or fixing the contaminants are possibilities to also use these potential resources. Cleaning of the sediment is however expensive, making it not economically competitive with other sources of aggregate (Cappuyns et al., 2015). However, Barjoveanu et al. (2018) concluded that leaving the contaminated sediment in a landfill is 10 times worse in terms of climate impact than fixing the contaminants in concrete. Additionally, landfill cost for polluted sediments are increasing with increasing land prices, costing between $120 and $1350 per tonne (Norén et al., 2020).

Another factor that hinders the use of dredged sediment in construction is time. Water saturation could be close to 100% when the sediment is dredged (Amar et al., 2021). The dredged sediment has to be dried first before it can be used in construction. Usually this is done by putting it in a plot of land surrounded by a wall to contain the dredged sediment. The time it takes to sufficiently dry the sediment depends on the weather and the composition of the sediment. A dewatering experiment in the Netherlands saw the water content drop from 65% to 44% over three months (Kox et al., 2021). Valuable land is taken up by this process, adding to the cost of the resource.

Another factor in the use of dredged sediment that should not be overlooked is the demand for the product. Building materials have to be safe and should not be at risk of failing. Consumers often have insufficient knowledge on products made with dredged sediment, causing them to be suspicious towards to quality of the products (Cappuyns et al., 2015). More readily available information about the quality, safety and environmental impacts could sway these opinions.

The demand for dredged sediment products can also be boosted by government incentives and a good regulatory framework. For example, EU regulations still classify dredged sediment as a waste (Crocetti et al., 2022). Standardising test for sediment compositions, implementing stricter rules on dumping dredged sediment on sea and in landfills, and making a regulated marked for dredged sediment would help make a promising economic sector (Bortali et al., 2022).

Widespread use of dredged sediment has some barriers to overcome. Some of the biggest barriers are the inconsistent composition of dredged sediments, contaminations with toxic chemicals, high water content, a lack of demand for the product and a lack of a regulatory framework and incentives from government.

9 Discussion & conclusion

Sediment is dredged from the bottom of rivers and harbours to keep marine traffic possible. Human activity surrounding those rivers and harbours are a source of pollutants that are ingrained in the sediment. All over the world hundreds of millions of cubic meters of sediment is dredged annually. A huge part of the dredged sediment is classified as waste and is dumped in sea or on land. There are however many valuable resources present in sediments that now go to waste. Dredged sediments consist predominantly of eroded rock and soil in the form of sand, silt and clay. Those are non-renewable resources used in applications ranging from building materials to plant growing mediums. Organic fractions and heavy metal present in dredged sediments can be used for beneficial purposes.

Concrete made from dredged sediment is weaker when there is organic matter present. Processes to solve this include filtering the organic matter out or burning the organic matter. These processes make dredged sediment more expensive than other sources of aggregate. Building materials made from dredged sediment are however often more sustainable. Bricks made from dredged sediment emit around 3 times less CO_2 than standard fired clay bricks. Construction materials are held to high standards, as buildings and roads should be safe. The variable nature of dredged sediment causes construction materials made from them to have different attributes. Other potential uses of dredged sediment don’t utilise the eroded rocks and soil, but the other components often found in dredged sediments. There are several promising techniques for heavy metal extraction, that could turn the process of cleaning dredged sediments profitable. Biogas can be made from the organic matter found in dredged sediment. Capturing the methane gas also lowers the potential greenhouse gas emissions from dredged sediments. When the organic matter and minerals are left in the dredged sediments, it can be used as a plant growth medium. However, pollution present in the sediment could result in plants that are not suitable for consumption.

The high cost of preparing dredged sediment for use makes it not economically competitive with other resources. Cost would go down with increased use of dredged sediments, as processes will become more efficient and new methods of cleaning will be tried. Regulations from the government could help streamline this process, by standardising test for sediment compositions and lifting the ‘waste’ classification of dredged sediments. Government policies focussing on dredged sediment as a more sustainable option could also increase the use of dredged sediment, as compagnies try to lower their greenhouse gas emissions.

Further research is needed to establish the greenhouse gas emissions related to the usage of dredged sediment. Not a lot is known about CO_2 and CH_4 emissions from dredged sediment, which makes a fair greenhouse gas emissions comparison between dredged sediment and virgin resources difficult to make (Kox et al., 2021). A large part of greenhouse gas emissions come from transport of the material (Zhou et al., 2021). Small transport distances are essential in making an application of dredged sediment more sustainable than alternatives. Research on applications for dredged sediment should focus on the area near to the extraction site. The production of bricks are an example of an application for dredged sediment that could be done close to the extraction site. Bricks made with sediment require a binder to solidify, usually in the form of cement. Cement takes up around 58% of the CO_2 emissions of dredged sediment bricks (Bhairappanavar et al., 2021). Fungus can be used as a binder of material and uses organic materials to grow (Ongpeng et al., 2020). Organic material often is abundantly available in dredged sediment, up to 30% by weight (Amar et al., 2021). The use of fungi could lower the CO2 emissions of dredged sediment bricks even further. Research needs to be done on how well fungi are in binding dredged sediment and how strong these bricks are compared to other building bricks.

Not all is yet known about contaminations found in dredged sediments. Constant et al. (2021) found a high concentration of microplastics in dredged sediment from the Aa river in France. This highlights the need to keep monitoring the contents of the dredged sediment. PFAS are another contaminant found in sediments around the world that are harmful and should be handled with care (Göckener et al., 2022; Goodrow et al., 2020). Further research is needed to establish the presence of microplastics, PFAS and other harmful contaminants in dredged sediments.

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