IMplementing MEasuRes for Sustainable Estuaries (IMMERSE)

WP 3. Measures: Defining pressures and solutions

Report for WP 3.3 Design solutions for managing contaminated sediments in the Göta älv

Authors: Anna Norén, Peter Norberg, Yvonne Andersson-Sköld, Sebastien Rauch and Ann-Margret Strömvall

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1. Introduction

Sediment needs to be regularly dredged and handled in the Göta älv (Göta River) estuary (Sweden), in the same way as at many other sites worldwide. However, sediment often has elevated levels of contaminants, such as metals and organotin compounds as for example tributyltin (TBT), originating from different anthropogenic activities in and around the water (HELCOM, 2009; OSPAR, 2011). Organotin compounds have demonstrated negative environmental effects even at low concentrations (Smith, 1978; European Commission, 2005) and are of worldwide concern for sediment stakeholders. In sediments from Swedish waters, contents of TBT of up to 10 mg/kg have been measured, with the highest contents reported for the Göta älv (Norén, 2021; Göta älvs vattenvårdsförbund, 2003; Brack, 2002). Although the use of TBT in boat paints has long been banned in the European Union, high levels are still found in marine and coastal sediments and remain a problem (Göta älvs vattenvårdsförbund, 2016). Ports have a regular need for dredging the waterways and the mooring areas to maintain sufficient water depth. This is essential to be able to manage port activities and is a responsibility as the owner of the sea infrastructure. From a port perspective, it is of great interest to find sustainable methods for handling contaminated sediments (Casper, 2008). Sediment quality differs between sites and therefore it is interesting to find ways to handle and treat sediment that can be transferred to other sites. In this report, the sediment management practices in Göta älv are investigated and the findings are discussed in the context of applicability to other sites in the North Sea Region. Designed solutions for evaluating the sustainability of sediment management methods are presented and the views of an international group of sediment stakeholders on the current sediment management and presented designed solutions are presented.

2. The Göta Älv Case Study

Introduction

The Göta älv (Göta River) is the largest river in Sweden (Göta älvs vattenvårdsförbund, 2016). The Göta älv area runs from Lake Vänern in the north to Gothenburg in the south. In the south, two-thirds of the river flow is in the Nordre älv (Nordre River) and one-third runs through Gothenburg, i.e., the Göta älv estuary. The Göta älv valley, and the city of Gothenburg, has a long history of anthropogenic activities such as settlements, shipping, ports, industries, and is surrounded by infrastructure including large roads and railroads that are causing contaminants being released into the environment. The river is used by many different actors with various interests. The archipelago is highly populated with commuters (ferries) and in the summer season, the population is increased due to tourism. The Göta älv and its catchment area show high species richness and many rare species live in the area. Several areas at the Göta älv and in the catchment area are included in the EU Natura network 2000 to prevent the reduction of biodiversity.

The Göta älv has been used as a water source since the late 1800s. Concentrations of environmental pollutants analysed in the water meet the drinking water requirements, but the contamination of faeces is a continued threat to the Göta älv as a raw water source, and the impact is still high. The Göta älv is classified as heavily modified water and the ecological potential is classified as unsatisfactory where the hydrology, regulations of the water flow are decisive (VISS, 2021). Already today, flooding occurs with mainly material damages and infrastructure failures. In the area, flood events are caused both by high precipitation and high seawater levels (Göta älvs vattenvårdsförbund, 2016). Also, the storm and sewage water systems have difficulties functioning under flood and storm events. Under such events the pollutant load to the Göta älv estuary is increased due to the first flush not passing the water treatment plant and that the contaminated land upstream, highly polluted roads, and urban areas, are flooded.

The Port of Gothenburg is Scandinavia's largest and most important port and is located in the Göta älv estuary. The port has over 11,000 ship visits per year from over 140 locations worldwide (Port of Gothenburg, n.d.). It is the only Swedish port with the capacity to cope with the largest modern, ocean-going container ships. Therefore, Gothenburg handles nearly 30% of Sweden's foreign trade, comprising 39 million tonnes of freight per year. The port has 13 km of docks situated on both sides of the estuary of Göta älv. Due to the large scale and importance of the port, dredging is necessary regularly to maintain sufficient sailing depth and to keep the highly complex infrastructure of the port.

Sediment in the Göta älv estuary

The bedrock of the Göta älv valley is dominated by gneiss with elements of diabase and granite. The Göta älv estuaries are characterized by low-lying areas with deep glacial and post-glacial clay deposits, at some places over 100 meters, which overlays friction soil and rock. Layers of silt and sand in the clay layers are common. Along the coastlines in the Göta älv estuary, there are also fillings, and the western parts are dominated by rocks. The annual transport of sediment in the Göta älv has been calculated to be over 120,000 tonnes (Göta älvs vattenvårdsförbund, 2016).

The sediment in the river contains contaminants of different origins. A contaminant of major concern in the river sediment is organotin compounds. This group of contaminants has been used in a range of applications since the 1920s, reaching a maximum production of 50 000 tons/year in 1996 (Bennett, 1996). Tributyltin (TBT)-containing paints were banned on all Swedish ships beside ocean-going vessels in 1993, however, large amounts of organotin compounds remain in the environment, especially in the port sediments due to the high persistence and very long time for degradation with a half-life time of 10–90 years in sediments (Viglino, 2004; Dowson, 1996).

TBT concentrations of 0.0 –10 µg/g have been reported on the Swedish west coast, with the highest concentrations at the Gothenburg port (Brack, 2002). Emissions from antifouling are also an important source of microplastics in marine sediment; wear from leisure boats only (ships unknown) results in up to 740 tons of microplastic annually (Naturvårdsverket, 2017). Another important source of pollution to the sediment is the urban runoff containing metals and organic pollutants (Markiewicz. 2020; Björklund 2011). High concentrations of particles, microplastics, metals, and persistent organic pollutants are frequently found in runoff from traffic environments. Polycyclic aromatic hydrocarbons, some of which are carcinogenic, were detected in total concentrations up to 21 mg/kg in stormwater sediment in Gothenburg (Strömvall et al, 2007). Urban sediments may also carry high concentrations of copper up to 250 mg/kg, and zinc as high as 1400 mg/kg (Karlsson et al, 2010). The antifouling paints used today are an environmental risk because they contain copper oxide as biocide and zinc oxide to control the erosion rate. It is therefore likely that concentrations of copper and zinc in marine sediments will increase depending on the growing use of antifouling, but also depending on the increasing inflow from urban runoff.

Existing and anticipated pressures

Climate change is expected to result in a sea-level rise by one meter until the year 2100 in the Göta älv (Bergström et al, 2011). Furthermore, extreme weather situations including storms and heavy rainfall will increase with an increased frequency of flooding events as a result. In the area, flood events are caused both by high precipitation and high seawater levels. The high seawater levels are caused by low pressure situations with westerly and high winds. Increased precipitation will increase the contamination load in the Göta älv estuary unless the capacity of the stormwater system and the water treatment plant is increased. One proposal to reduce the probability of flooding in the central parts of Gothenburg is to build barriers in Göta älv, i.e., one barrier upstream the river south of the branching to Nordre älv and one barrier downstream, west of the bridge Älvsborgsbron. Both the sea level rise alone, increased extreme weather events, and measures taken to reduce the risk may have a non-wanted impact on the environment and economic as well as social consequences are expected.

The international trading at sea is annually increasing and is expected to increase. Transportation vessels become larger, which requires a deeper waterway. Currently, dredging needs to be done approximately every 3 to 5 years on a large scale in the Port of Gothenburg. On top of this, there is also a continuous amount of minor dredging activities and construction work, together with large infrastructure projects, with a need to handle contaminated sediments. The major dredging projects are resulting in around 200 000 m^3 sediment/dredging cycle and it is estimated that around 75% of the sediments are polluted (Nielsen Gulis, 2019). The pollution levels are too high to be landfilled, dumped to sea, or used in other ways without some remediations.

In Gothenburg, there are currently several ongoing activities that will affect the Göta älv estuary. For instance, large infrastructure investments such as the railway project Västlänken with several tunnelling projects involving great excavations could also affect the estuary in several ways. Already in the construction phase, there will be effects as the excavated material will need to be utilized or disposed of. Regardless of which management option that will be applied it will affect the environment and maybe also the appearance of the estuary and city.

3. Method

Literature studies and interviews with local port authorities were done to establish the current sediment management practices in the Göta älv. A transnational estuary exchange lab (TEEL) was held with sediment stakeholders from the Göta älv case study, but also other sediment stakeholders from the North Sea region involved in the Immerse project, to discuss sediment management (Immerse, n.d.). Examples of stakeholders present at the TEEL were port authorities, universities, research institutes, consultants, municipal boards, county administrative boards, and governmental agencies working with sediment management. The perceived views of the stakeholders were collected and compiled.

To assess economic and environmental impacts related to different management alternatives integrated assessment and life-cycle assessment (LCA) methods were developed and tested using data from the Göta älv case study as well as other sites (Norén et al, 2020; Svensson et al, 2022). The studied scenarios included combinations of deep-sea disposal, landfills, metal recovery, construction with sediment, and monitored natural recovery. An LCA was done by using SimaPro® EPD software and the Ecoinvent database together with real site data from the Göta älv case study. The full methodology is presented in the open access articles by Norén et al 2020 and Svensson et al 2022. The scientific articles are also available in this report in Appendix 1. Please note that the existing pilot on stabilisation of dredged masses in the Port of Gothenburg and the developed method for degradation of TBT and recovery of metals and polluted sediments on a laboratory scale is fully assessed in WP 4.3.

4. Results and discussion

Sediment management

As stated in the case study information, maintenance dredging of approximately 200 000 m^3 is done every 4–5 years in the Göta älv estuary. The masses mostly consist of finer particle sizes, such as clay and slit. Currently, the handling of sediments and contaminated sediments are done mainly by landfilling and bottom deposition by sea or in the riverside. However, a large quantity of the sediment dredged between 2018–2025 will be used in the construction of a new port terminal (Port of Gothenburg, n.d.). The quantity of sediment used for each management option varies between the dredging operations and depends on the sediment contamination, regulation, and costs associated with different alternatives. In the following section current sediment management practices used in the Göta älv estuary are presented as well as current research in sediment management and possible future management practices. All these alternatives were presented and discussed during the TEEL.

Current practices

Reuse of contaminated dredged sediments

A stabilisation and solidification method (s/s method) is used for the utilization of the dredged sediment and is under evaluation in a pilot project at Arendal in the port of Gothenburg. The s/s method has been developed and commercialized to be used in full scale. The method has previously been used in the Port of Gävle (Sweden) on a large scale (SGI, 2011). In the Port of Gothenburg, an entirely new terminal will be constructed of contaminated sediments stabilised by adding binders consisting of cement and granulated blast furnace slag. The area is 220 000 m^2 in size and has a maximum water depth of 10 m. The concentrations of TBT are high in the sediment; therefore, permits are set regarding TBT leaching from the construction. Therefore, finding the optimal binder recipe is crucial and has been done in steps to lower the quantity of TBT from being released. Laboratory tests and evaluation of geotechnical properties and leaching of contaminants was done to find an ideal mixing ratio. Later, the field pilot-test was performed, where approximately 10 000 m^3 of contaminated sediment was stabilised and placed behind an embankment. Environmental and geotechnical properties have been monitored according to a monitoring programme.

The s/s method enables the reuse of contaminated dredged sediments, which have previously been considered as waste, through treatment and conversion into material useful for building foundations. A study examined how well the method works concerning mechanical strength and leaching of TBT, as well as in an ongoing project in the port of Gothenburg, and whether the s/s method can be considered as a part of a sustainable future (Thulin, 2018). However, as the method is relatively new and results from the long-term effects are lacking it is difficult to evaluate the sustainability of the method. In addition, the most common binder, cement, cannot be considered economically or environmentally sustainable because of its environmentally damaging manufacturing process and high cost. At the same time, follow-ups on finalized projects indicate that the long-term prognosis appears reasonable. Attempts to replace cement completely or partially with other binders are ongoing. Although the method does not reduce the total pollution on earth, it is an effective way of limiting the mobility of the pollutants and reducing the exposure area to the environment.

On large scale, when using the s/s method, contaminated sediments are utilized for building new port areas instead of disposing of the sediments on land or at sea. Therefore, there are benefits for the environment and costs are reduced, e.g., improvement in ecological habitats, disposal capacity maintenance dredging works, and minimizing spreading of contaminants from sediments.

The conclusion is that the s/s method can be considered well-functioning and sustainable compared to different disposal alternatives. It is rather a question of which approach we take on regarding questions of sustainability and societal development. Even if the s/s-method has some shortcomings and has potential for improvement it is already a better alternative than treating all contaminated dredged sediments as waste that will end up in landfills or as deep-sea disposal.

Water disposal

Currently, sediments from the Port of Gothenburg are deposited either out at sea or in previously used port basins (Nielsen Gulis, 2019). If dredged sediments contain little to no contaminants this method is often a cheap solution. Contaminated sediments are in most cases not allowed to be dumped to a deep-sea deposit as sediment deep-sea deposition needs legal authorization in most countries. In the Göta älv case study, a deep-sea disposal site, SSV Vinga (Vinga), is used. Vinga has been used since the 1980s and the current requirement demand that the sediment that is to be disposed of there does not exceed measured pollutant levels at the site. Also, it is crucial not to dispose of too large sediment quantities if the ecosystem should be given a chance to recover. Frequent and large dispositions could cause permanent damages to the site, and recovery for biota might be difficult.

Landfill

The use of contaminated sediments is very limited and currently, possible remediation methods are few, often associated with high costs and have high land area demand. In the Port of Gothenburg, dredged sediment that contains contaminants (such as e.g., TBT, PCB, and mercury), at levels that do not allow the masses to be disposed out at sea. Recent changes in the European waste legislation have resulted in a decreased number of available landfills and increased landfilling costs. Additionally, marine sediment is more problematic in comparison to e.g., soil from a waste management perspective, as sediment typically contains high amounts of water with high salinity. This puts more demand on a landfill in comparison to e.g., soil masses, which makes the number of available landfills scarce, and the transportation distance longer to reach these landfills. Landfills occupy the land during the active phase, but the landuse is limited also after closure and the landfill area must be maintained in undefined time.

Potential solutions

Other more innovative management options have been researched on sediment from the port of Gothenburg (Norén, 2021). Here, different alternatives to lower the content of TBT and metals in the sediment have been investigated. The methods used included leaching (Norén et al, 2021), oxidative methods (Norén et al, 2022), and electrolysis combined with stabilisation (Norén et al, under publication). By lowering the contaminant level, the sediment may be used in more applications. Additionally, if metals would be recovered from the sediment they could be used in society and potentially yield a small reduction in management cost. However, the salinity of the sediment is problematic as it limits the possible uses. In the Göta älv estuary, the sediment consists of fine particles, which further limits the possibility to use the sediment. However, in many other countries, the sediment consists of coarser grain sizes which facilitate contaminant removal and make it possible to use the sediment in other applications. In laboratory studies using sediment from the Göta älv, the TBT content was reduced by 64% and metals such as copper by 45% and zinc by 40% (Norén et al, 2022). The methods could be further developed and altered to reach a higher removal rate and be optimized for other types of sediment.

Results from stakeholder workshop

A transnational exchange lab was held in Gothenburg 12-13 June 2019, where sediment stakeholders met and discussed sediment management and ongoing research in Gothenburg. Key messages from these conversations are presented here, and for the full report, see the document IMMERSE Implementing MEasuRes for Sustainable Estuaries Conference Report Transnational exchange lab 12-13 June 2019. 1st IMMERSE Transnational Estuary Exchange Lab,12-13 June 2019, Gothenburg, Sweden (IMMERSE, n.d.)

Regarding the contamination of the sediment, it was identified that there is a need to work both with treating the sediment as well as with limiting the release of pollutants into the environment. This could be done by phasing out dangerous substances but also by preventing the release of them already at the source. Further, it was identified to be important to work with closing material loops, trying to recover e.g., metals from wastewater, but also design products with the circular economy in mind. If possible, in-situ treatment techniques could preferably be used before dredging is done, to minimize the need to treat the sediment on land.

Specifically, for the management of sediment, it was important to continue with technique development and transferring of knowledge so that innovative new techniques come to use and so that lessons are learned. To make sure the techniques are put to use, it is important to consider cost-effectiveness and stakeholders' willingness to pay. LCA was identified to be a suitable tool to compare different options on environmental impact. During the meeting, the option of using s/s was discussed, and it was identified by the stakeholder as a convenient method as the sediment could be used, instead of being disposed of. However, this is a relatively new method in Sweden, and the long-term effects need to be further studied to be perceived as a safe method and to ensure that contaminants are locked in. Additionally, the option of s/s sediment was not seen as a long-term solution, as the current usage is limited to construction in ports. In order to put new technologies to use, it is important that the techniques are perceived as safe, but it is also important to have clear regulations and legislation to facilitate decision-making and roles and criteria.

Design of solutions for the management of contaminated sediment

Sediment management is a complex issue, and a need for a generic flexible evaluation tool was identified during the TEEL meeting. An integrated assessment method was developed and complemented with LCA to evaluate the economic and environmental impacts caused by different sediment management scenarios. In the model, sediment from different sites was used to assess the applicability to be used in different situations. The model was designed to be a general and applicable stepwise guide, in which important parameters to be considered are introduced (e.g., local restrictions, costs) (Figure 1). The studies by Norén et al 2020, and Svensson et al 2022, investigated the following management scenarios, and a combination of different management strategies was used: landfill (for hazardous (HW) and non-hazardous waste (NHW)), deep-sea disposal, monitored natural recovery, construction, electrolysis. However, other management options could be implemented and used in the model as well.

In the study by Norén et al 2020, the first step in the assessment (Figure 1) is that the sediment quality parameters are investigated, and the sediment could be assigned different classifications depending on the local regulations. In the second step, sediment management strategies could be suggested and evaluated based on the results from the initial sediment characterization. This makes it possible to do cost estimations for the management alternatives of interest in step three. In the fourth step, the costs of different options are compared, and here, the potential of doing metal recovery was applied. In the fifth step, the environmental impacts of the investigated management strategies were investigated by using multicriteria analysis, with results from a literature review on the management strategy. Here, short- and long-term effects were evaluated separately, as they could vary greatly. In this step results from an LCA could also be implemented. In the final step, a comparative analysis is done by weighing together results from the economic and environmental aspects.

In the LCA it was seen that construction contributed to the largest release of CO_2 in comparison to deep-sea disposal and landfilling. The large emissions are mainly associated with the use of cement in the mixture. With the combination of first doing metal recovery with electrolysis and then performing s/s on the residue, it was seen that metal recovery was more beneficial to be done on more contaminated sediment, as e.g., more virgin metal resources could be saved. However, a higher release of CO_2 was seen for more contaminated sediment if the sediment was to be put on a landfill with and without the combination of deep-sea disposal. This is due to longer transportation distances for heavily contaminated sediment, which requires stricter landfill management, and this type of landfills are few. Deep-sea disposal had a low CO_2 release as transportation on barge results in a lower climate impact in comparison to transportation using trucks.

However, when including other environmental factors in the evaluation, it was seen that many of the management options had both counteractive and synergistic effects. It was also seen that the environmental effects differed over time. For instance, in cases where no dredging is required letting the sediment remaining in the water may be most beneficial but in the long-term it may be better to remove or treat the sediment in-situ.

This highlights that the level of contamination has a large impact on both economic and environmental parameters. Also, local regulations and restrictions will impact the suitability of the different options. It was seen that it might be both economically and environmentally interesting to extract metals from sediment, especially as landfill prices are increasing and the metal prices are increasing. However, currently, there is a need for further method development to gently extract metals without causing a decrease in sediment quality after treatment.

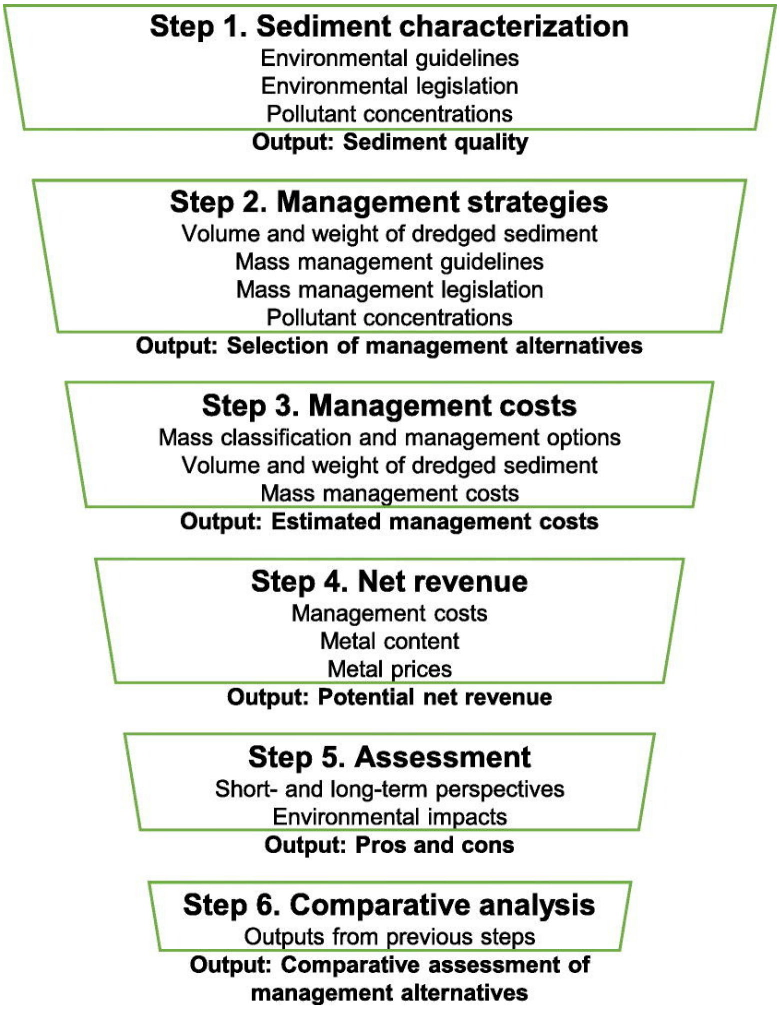

Figure 1 Overview of the steps included in the integrated assessment method (Norén et al, 2020).

5. Summary

Sediment from the Göta älv estuary has historically mainly been managed by disposal, at a landfill, by sea, or in previously used basins. Currently, the option of using the dredged sediment in construction is also used. This technique was perceived as a more positive option by the stakeholders in comparison to the options related to disposal. A need to treat the sediment as well as minimize the new input of pollutants into the river was identified as important measures by the stakeholders. The developed techniques for contaminant removal were perceived as positive, however, a concern about the transferability of the techniques to other sites and sharing of knowledge was raised. Additionally, the need to investigate both economic and environmental impacts related to new and old techniques was identified. Here, the developed multicriteria analysis (MCA) and LCA were perceived as useful tools to identify the best sediment management solution.

A conclusion from the stakeholder workshop and the evaluation of management options is that no solution is optimal for all ports. Instead, it is better to do site-specific solutions. The developed integrated assessment tools could be useful for stakeholders to use early in the decision-making process to get an overview and identify possible solutions, and when combined with LCA, also identify where measures could be done to lower the management alternatives' impact on e.g., climate change.

The sediment investigated in these studies consists of fine grains, mainly silt, which has low geotechnical qualities. In other sites, where coarser sediment is found, more direct use might be possible. As the methods developed for LCA and MCA are generic they could be used for other case studies, as well as including other management scenarios. Regardless of the site location and conditions, site-specific data should be used to get a reliable result.

6. Further studies

Further studies will be done in the IMMERSE work package (WP) 4.3. Assess existing pilot on stabilisation of dredged masses and developed methods for recovery of metals and treatment of polluted sediments in the Göta älv. In this work package laboratory analysis, functionality tests of samples, bottom sediments analysis, and LCA will be conducted for the ongoing pilot in the Göta älv. This section will include studies of treatment methods and recommendations for large-scale implementation, plus scientific articles on metal recovery, to share results broadly. The results from the work packages 3.3 and 4.3 will be used as a basis and further developed in the following projects:

- IMMERSE extension project 2021–2023 – Develop innovative rain gardens to filter and degrade microplastics.
- SGU/RUFS – Government missions on polluted sediments 2021–2022. Development of a New Method for the Treatment of Contaminated Sediments with Photoelectrocatalytic Degradation.
- FORMAS post-doc project 2022–2024 – Sustainable Utilisation and Treatment of Contaminated Sediments.

7. References

Bennett (1996). Industrial manufacture and applications of tributyltin compounds in Tributyltin – Case Study of an Environmental Contaminant , pp. 21 – 61. Publisher: Cambridge University Press

Bergström, Andréasson, Losjö, Stensen, and Wern (2011). Hydrologiska och meteorologiska förhållanden i Göta älvdalen, slutrapport, slutlig version. 3 (sgi.se)

Björklund (2011). Sources and fluxes of organic contaminants in urban runoff. PhD thesis Chalmers University of Technology ISBN 978-91-7385-480-1.

Brack (2002). Organotin Compounds in Sediments from the Göta älv Estuary. Water, Air and Soil Pollution 135, 131-140.

Casper (2008). Regulatory frameworks for sediment management. Sediment Management at the River Basin Scale, vol. 4, P. N. Owens, Ed. Sustainable Management of Sediment Resources: Elsevier, 2008, pp. 55-81.

Dowson, Bubb, and Lester (1996). Persistence and Degradation Pathways of Tributyltin in Freshwater and Estuarine Sediments. Estuarine, Coastal and Shelf Science, vol. 42, no. 5, pp. 551-562.

European Commission (2005). Common Implementation Strategy for the Water Framework Directive Priority Substance No. 30 Tributyltin compounds (TBT-ion). Environmental Quality Standards (EQS) Substance Data Sheet, Brussels, 15 January 2005 vol. Final version.

Göta älvs vattenvårdsförbund (2016). Fakta om Göta älv. En beskrivning av Göta älv och dess avrinningsområde nedströms Vänern 2015. Report. [In Swedish]

Göta älvs vattenvårdsförbund (2003). Miljögifter i och kring Göta älv – sammanställning av undersökningar av vatten, sediment, biota och utsläpp . [In Swedish]

HELCOM (2005) Standards (EQS) Substance Data Sheet (2009). Brussels, 15 January 2005 2005, vol. Final version.

HELCOM (2009). Hazardous substances of specific concern to the Baltic Sea - Final report of the HAZARDOUS project. Balt. Sea Environ. Proc. ISSN 0357-2994, 2009.

IMMERSE (n.d). Conference report. Transnational Exchange Lab. 12-13 June 2019. Gothenburg, Sweden.

Karlsson, Viklander, Scholes and Revitt (2010). Heavy metal concentrations and toxicity in water and sediment from stormwater ponds and sedimentation tanks. Journal of Hazardous Materials 178, 1–3, Pages 612-618.

Markiewicz (2020). Colloidal Organic Pollutants in Road Runoff: Sources, Emissions and Effective Treatment Technologies. PhD thesis Chalmers University of Technology ISBN 978-91-7905-335-2.

Naturvårdsverket (2017). Mikroplaster. Redovisning av regeringsuppdrag om källor till mikroplaster och förslag på åtgärder för minskade utsläpp i Sverige. Rapport 6772. June 2017.

Nielsen Gulis, Nikol (2019). Port of Gothenburg [PowerPoint slide]. IMMERSE 1st Transnational Exchange Lab. 12 June 2019. Gothenburg, Sweden. Available at 03_NielsenGulis_Powerpoint IMMERSE TEL Goteborgs hamn copy (northsearegion.eu)

Norén, Karlfeldt Fedje, Strömvall, Rauch, Andersson-Sköld (2020). Integrated assessment of management strategies for metal-contaminated dredged sediments – What are the best approaches for ports, marinas and waterways? Science of the Total Environment. 76, 135510.

Norén (2021). Management and Treatment of Organotin and Metal Contaminated Dredged Sediment. PhD thesis Chalmers University of Technology ISBN 978-91-7905-537-0.

Norén, Karlfeldt Fedje, Strömvall, Rauch, Andersson-Sköld (2021). Low impact leaching agents as remediation media for organotin and metal contaminated sediments. Journal of Environmental Management. 282, 111906.

Norén, Lointier, Modin, Strömvall, Rauch, Andersson-Sköld, Karlfeldt Fedje (2022). Removal of organotin compounds and metals from Swedish marine sediment using Fenton's reagent and electrochemical treatment. Environmental Science and Pollution Research.

Norén, Strömvall, Rauch, Andersson-Sköld, Modin, Karlfeldt Fedje (under publication). Stabilization and solidification of organotin contaminated sediment: Electrolysis pretreatment, leaching, and compression strength.

OSPAR Commission (2011) Background Document on Organic tin compounds. Hazardous Substances Series.

Port of Gothenburg (n.d.) New Master Plan marks out the future at the Port of Gothenburg. Available at New Master Plan marks out the future at the Port of Gothenburg Accessed 2022-01-20

Port of Gothenburg (n.d.) New terminal at Arendal. Available at New terminal at Arendal (portofgothenburg.com) Accessed 2021-09-21

SGI (2011). Vägledning för nyttingörande av muddermassor i hamn- och anläggningskonstruktioner.Stabcon.

Smith (1978). Toxicological data on organotin compounds in International Tin Research Institute, 1-10. ITRI Publication No. 538, Middlesex, England.

Strömvall, Norin, and Pettersson (2007). Organic contaminants in urban sediments and vertical leaching in road ditches. In Highway and Urban Environment: Alliance for Global Sustainability Book series, Vol. 12, pp235 – 248, Morrison, G.M.; Rauch, S. (Eds.)

Svensson, Norén, Modin, Karlfeldt Fedje, Rauch, Strömvall, Andersson-Sköld (2022). Environmental assessment of management options for dredged sediment – a combined LCA and MCA approach. Environmental Management. 138, 30.

Thulin (2018). Livscykelanalys av förorenade sediment. BSc Thesis Department of Mechanical Engineering Blekinge tekniska högskola.

Viglino, Pelletier, and St-Louis (2004). Highly persistent butyltins in northern marine sediments: along-term threat for the Saguenay Fjord (Canada). Environ Toxicol Chem, vol. 23, no. 11, pp. 2673-81, Nov 2004.

VISS, 2021. Vattenkartan. Available at Vattenkartan (lansstyrelsen.se) Accessed 2021-09-21

8. Appendix 1 (pdf files with the papers)

Paper I. Norén, Karlfeldt Fedje, Strömvall, Rauch, Andersson-Sköld (2020). Integrated assessment of management strategies for metal-contaminated dredged sediments – What are the best approaches for ports, marinas and waterways? Science of the Total Environment. 76, 135510.

Paper II. Svensson, Norén, Modin, Karlfeldt Fedje, Rauch, Strömvall, Andersson-Sköld (2022). Environmental assessment of management options for dredged sediment – a combined LCA and MCA approach. Environmental Management. 138, 30.