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Life Cycle Assessment of Management Scenarios for Dredged Sediments: Environmental Impacts Caused during Landfilling and Soil Conditioning

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Abstract: The management of dredged sediments is a challenging issue since it involves the interconnection of complex economic, social, technical and environmental aspects. The EU LIFE SURE project aimed to apply a more sustainable dredging technique to Malmfjärden Bay in Kalmar/Sweden (a shallow urban water body with a high content of nutrients) and, additionally, it involved beneficial uses for the dredged material, in line with the circular economy concept. To achieve this, a life cycle assessment (LCA) study was carried out to assess the potential environmental impacts associated with two scenarios: sediment landfilling (S1) and soil conditioning (S2). This LCA study also aimed to evaluate and compare the costs related to each scenario. S1 contemplated the construction and operation of the landfill for 100 years, including the collection and discharge of leachate and biogas. S2 included the use of sediments in soils and the avoidance of producing and using fertilisers. Results showed that (S2) soil conditioning (total impact: −6.4 PE) was the scenario with fewer environmental impacts and the best economic evaluation. The S2 scenario was mainly related to the positive environmental savings produced by reducing fertiliser consumption (which also avoided purchase costs). However, S2 was also linked to potential negative effects associated with eutrophication and toxicity categories of impacts due to the possible spread of nutrients and pollutants in terrestrial and aquatic environments. In order to mitigate this problem, the sediments could be pre-treated to reduce their risk of pollution. Moreover, the main impact of the landfilling scenario (S1, total impact: 1.6 PE) was the emission of global warming-contributing gases during the operation of the facility. Implementing the soil conditioning scenario was therefore recommended, in line with the aim of the LIFE SURE project. Finally, it was recommended that LCA studies should be applied more often in the future when selecting beneficial uses for dredged sediments. The decision-making process is facilitated when the positive and negative impacts produced by each handling option are considered.

Keywords: dredged sediments; LCA; soil conditioning; landfilling; sustainability; circular economy

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1. Introduction

The dredging of sediments is a common practice to maintain proper water levels in harbours and restore aquatic ecosystems. Large amounts of dredged material are generated annually and Europe alone produces around 200 million m^3 of dredged sediments annually [1]. Traditional disposal methods include discharge into open oceans and landfills and both strategies are related to the possible contamination of ecosystems and the loss of valuable resources [2]. The open ocean disposal, for instance, poses health risks to marine ecosystems and, therefore, the method is banned in several countries [3]. Additionally, landfills are recognised for their high requirement of area, loss of valuable materials and production of harmful by-products like climate change emissions and contaminated leachate [4].

As an alternative, dredged sediments could be employed for beneficial uses to avoid traditional methods and incentivise the implementation of circular economies. Depending on its composition, dredged material could be employed for different purposes, avoiding the mining of primary raw material and contributing to stopping the depletion of natural resources [5]. The selection of beneficial uses depends on the characterisation of the material and local conditions, such as the demand [5]. The composition of dredged sediments varies according to the history of discharges to water bodies. However, common components are sulphide, chloride, metals and organic compounds. Organic matter and nutrients are also common components that justify using this material in soil conditioning projects [6].

Dredged sediments could be employed for soil conditioning since the nutrient and organic matter content in these sediments could improve the chemical status of soils. Physical properties, such as particle size distribution and water holding capacity, could also be improved [5]. This type of use could help recover degraded and deforested land resulting from population pressure [7,8]. Additionally, phosphorous is a limited resource on Earth [9] and more sustainable sources of this element will be required in the future. After exhausting the existing reserves, no more mines will be available to supply the demand for fertilisers [10]. Moreover, the element is only located in a few countries, causing a geopolitical situation that could restrict the availability of phosphorous in several parts of the world [11]. Dredged sediments are, therefore, a potential source of phosphorus when using the material in soil conditioning.

Nevertheless, implementing beneficial uses for dredged material is challenging due to problems like compliance with strict legislation, acceptance of stakeholders, achievement of favourable cost effectiveness and technological issues [12]. Moreover, dredged sediments are also associated with contaminants that could possibly impact ecosystems, increasing the risk to the environment and human health [13]. Some metals in particular could be toxic to the environment [6]. Anthropogenic activities like mining, agriculture, shipping, harbours and industry in general are the main sources of toxic metals [14]. It is important to assess the risk of leaching metals while using dredged sediments before selecting the type of use. Hence, more decision tools are required to help decision makers select effective beneficial uses for dredged material.

The life cycle assessment (LCA) is a tool to evaluate the environmental impacts caused by products, including the extraction of raw materials until the final disposal. The methodology is also currently employed to evaluate waste management scenarios, facilitating the calculation of environmental impacts caused by the different handling strategies. Studies such as Cheela, et al. [15], Hadzic, et al. [16], Chazirakis, et al. [17], Majeed, et al. [18] and Ziegler-Rodriguez, et al. [19], among others, employed LCA to assess alternatives to handle domestic waste management options.

Another application of LCA refers to the evaluation of the management of dredged sediments. Pasciucco, et al. [20], Hou, et al. [21], Barjoveanu, et al. [22], Sparrevik, et al. [23] and Hossain, et al. [24] employed the methodology to calculate the environmental impacts caused by landfilling or remediation methods such as soil washing, electrokinetic removal and solidification/stabilisation. Additionally, Bates, et al. [25] studied the environmental impacts caused by open water and upland disposal. The only studies reporting the environmental impacts produced while using the sediments to recover nutrients were Legua, et al. [26] and Zhou, et al. [27]. The first study [26] focused on the assessment of using dredged sediments as a plant-growing substrate to cultivate strawberries. The second study [27] included the assessment of the alternative of using sediments as a soil conditioner. As shown, investigations focused on the impacts caused by different strategies for handling dredged material are limited and focus more specifically on the treatment stages. More studies are required to assess the impacts that are caused when using dredged sediments for beneficial purposes in the circular economy.

The sustainability of a certain activity is only achieved when environmental, social and economic aspects are contemplated together. Therefore, there is a need to implement more studies investigating tools that also involve social and economic aspects. The aim of this study was to carry out an LCA and an evaluation of the cost of a traditional disposal method and a beneficial use option for dredged material as a contribution to the lack of decision tools available for the assessment of handling scenarios for dredged material. The case study used was the European Union LIFE SURE dredging project conducted in Malmfjärden Bay, located in Kalmar, Sweden. The studied scenarios regarding the destination to be given to the dredged sediments are landfilling and soil conditioning.

2. Materials and Methods

2.1. Study Site

Kalmar city is located in southeast Sweden and Malmfjärden Bay is in the city centre (56°66′ N, 16°36′ E) (see Figure 1). The water body creates a beautiful landscape highly important for the municipality since it hosts several recreational activities such as canoeing and walking. Moreover, the bay frequently receives migration birds, and fish are also present. The inlet to the bay is untreated runoff collected from the neighbouring areas (mainly houses and commercial areas), and an old dumpsite is located a few kilometres from the bay. The bay is currently shallow (water level sometimes less than 0.6 m) and shows a high concentration of nutrients and slight pollution with metals [28]. Similarly, the sediments from the bay contain high contents of nutrients and medium−low contents of metals [29]. Organic pollutants are not a concern of the material. Moreover, the sediments are mainly constituted of silt (60–70%) and clay (10–20%) and present with a low content of sand (10–20%) [29].

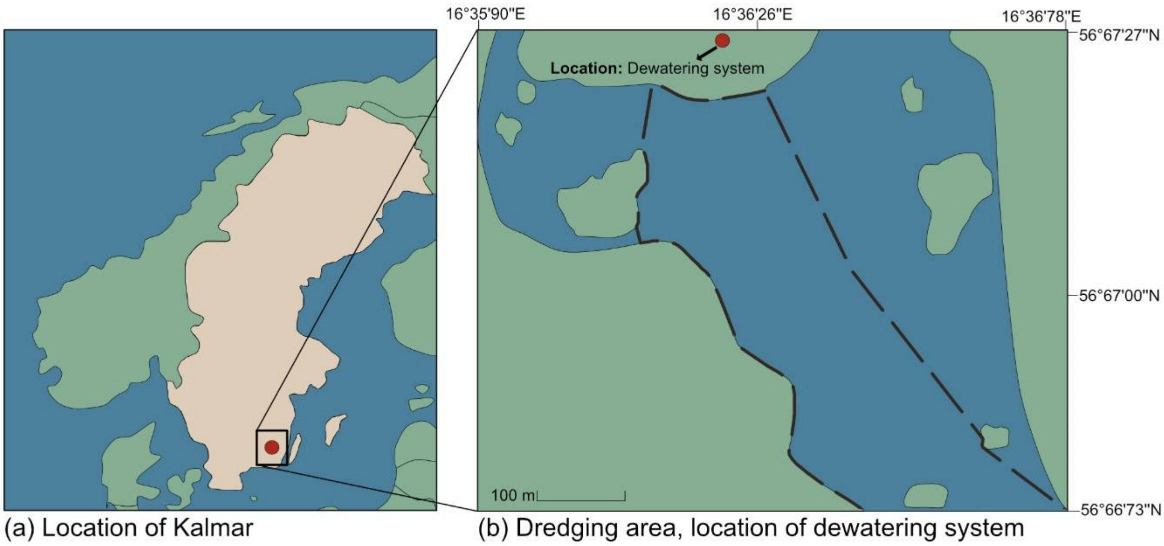

Figure 1. Location of Malmfjärden Bay, planned dredging area (dotted area) and dewatering system.

Additionally, a significant area of the region around Kalmar is dominated by agricultural land, with maise, wheat and beans being the major crops. Moreover, there is a landfill (Moskogen) located 20 km from central Kalmar.

2.2. LIFE SURE Project and the Innovative Dredging Technique

The municipality of Kalmar and Linnaeus University started a European Union dredging project (LIFE SURE) in 2019 in Malmfjärden to avoid the water body becoming a wetland. The initiative aimed to develop a more sustainable dredging technique that does not resuspend particles from the bottom and to employ the dredged material for beneficial uses. The use of the dredged sediments is important to incentivise the implementation of circular economic projects in the region and other European state members. The dredged material is extracted from the bay and pumped into a dewatering system. It consists of an equalisation tank used to homogenise the quality and quantity of the material and geobags for its dewatering.

2.3. Characterisation of the Sediments

The characterisation of sediments from Malmfjärden was carried out by employing samples obtained from the dewatering system. The samples were manually taken from the geobags and three different samples were sampled and used for analysis. The sampling events occurred in May 2020, July 2020 and April 2021. The samples were analysed in duplicates at certified laboratories (Eurofins, Lidköping, Sweden and SGS Analytics, Linköping, Sweden). The measured parameters were As, Ba, Pb, Cd, Co, Cu, Cr, Mo, Ni, Zn, V, Al, Fe, K, Mg, Mn, Ca, Na, N, P, S, Cl, ammonium, total organic carbon (TOC), organic content and compounds and pH. Elements were analysed following the standard SS-EN-ISO-11885 [30]. After digestion, the extract was analysed using inductively coupled plasma atomic emission spectroscopy (ICP-AES). The organic compounds were measured using a gas chromatography−mass spectrometry (GC−MS). Total nitrogen, ammonium, chloride and TOC were analysed following the standards SS-EN 16169:2012 [31], standard method 1998-4500 [32], SS-EN ISO 10304-1:2009 [33] and SS-EN 15936:2012 [34], respectively.

Moreover, the pH was measured after obtaining a saturated extract (mixing 10 g of dried sediment with 25 mL of deionised water for 60 min). The pH was measured on the supernatant using a pH meter (HQD field case, Hach Lange–Loveland, CO, USA). Finally, the water content was measured by drying the sample at 105 °C until no change in the weight of the sample was detected (SS-EN 12880:2000 [35]). After, the organic content was measured following SS-EN 15169:2007 [36] (loss on ignition test). The remaining sample was put into an oven at 550 °C until no change in weight was detected. The average values of all parameters were employed for the LCA model.

2.4. LCA Methodology

A comparative LCA was calculated following the methodology SS-EN ISO 14040:2006 [37], which includes the following phases: (i) goal and scope definition; (ii) inventory analysis; (iii) impact assessment; and (iv) interpretation. The assessment was carried out using the waste management-dedicated software EASETECH v3.3.5 (Technical University of Denmark (DTU), Lyngby, Denmark) [38].

2.4.1. Aim and Scope

The aim and scope of the study were defined after close contact with the project manager and personnel from the LIFE SURE project. The objective of the work was to provide a decision tool to determine the optimal (causing fewer environmental impacts) way to handle the sediments produced in the project. The option to employ the dredged material to recover nutrients has been studied and contemplated before [29,39]. Therefore, the aim of this study was to calculate the environmental impacts caused when using sediments from Malmfjärden as a soil conditioner. The results were compared with the traditional approach of landfilling the material.

2.4.2. Functional Unit and System Boundary

The functional unit for the analysis was 22 tonnes of sediment, which was the total amount of sediment dewatered in one geobag used in the LIFE SURE project. The unit was selected to calculate the total environmental impact caused each time a bag is generated. The amount was calculated with the volume of a geobag, which is 22 m^3 multiplied by the approximate density of the dewatered sediment (approximately 1000 kg m^{-3}).

The system boundary for the assessment was set by only selecting the activities related to handling treated sediments. The impacts caused while dredging and treating the dredged material are equal in all scenarios. Therefore, these activities were excluded from the system boundary, represented in Figure 2.

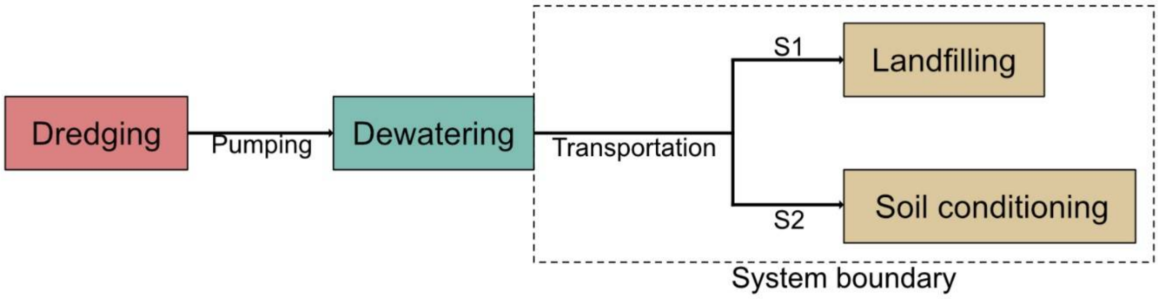

Figure 2. System boundary for the LCA. The system boundary is shown on the dotted rectangle.

2.4.3. Scenarios

The scenarios considered the traditional approach of landfilling the sediments (S1) compared to the option of using the material as a soil conditioner (S2). The steps of each scenario are shown in Figure 3. Both scenarios contemplated transporting the material from the treatment site to its final disposal or use (S1.1 and S2.1 for landfilling and soil conditioning, respectively).

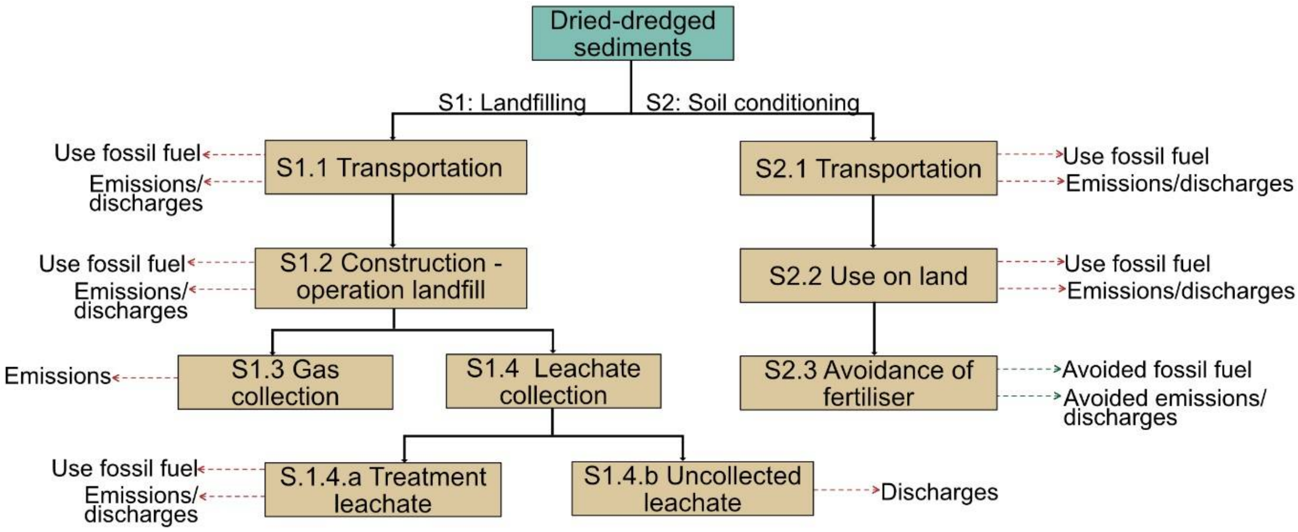

Figure 3. Steps of each scenario included in the assessment. Landfilling: S1 and Soil conditioning: S2.

Additionally, the landfilling scenario included the calculation of impacts caused while constructing the facility and carrying out its operation for 100 years (S1.2). The materials and energy used for both phases were accounted for in the step. S1 also included the calculation of environmental impacts caused by the production of leachate (between 500–1200 mm year^{-1} under average annual precipitation) (S1.4). Its collection was included, assuming a collection rate of 99.9% for the first 80 years and 87% for the remaining 20 years (according to the average performance of a functional landfill). The treatment of the collected leachate was contemplated, including primary and secondary treatments (with biological removal of N) (S1.4.a). The discharge of uncollected leachate was also included (S1.4.b). It was assumed that both treated and non-treated leachate were discharged into surface water bodies. The production of biogas (methane and carbon dioxide) was the final contemplated step of the scenario (S1.3). The scenario did not contemplate energy generation using biogas since, in Sweden, it is forbidden to landfill organic waste. Therefore, the production of biogas is reduced, and the landfills currently do not have facilities that produce energy from biogas.

After transportation, the second scenario contemplated the environmental impacts caused while spreading the sediments into agricultural fields (S2.2). It was assumed that the soils were sandy loam and the rotation of the crops was average compared to Scandinavian standards. Moreover, the scenario assumed that the application rate of nitrogen was below the maximum plant uptake. The fate of carbon and nitrogen was simulated by the model Daisy [40]. Finally, the impacts caused by the avoidance of using mineral fertiliser were included as the last step of the scenario to calculate the savings on environmental impacts (S2.3). The step assumed the same type of soil, crop rotation and N-application rate as those used when applying the sediments. The substitution was based on a 1:1 scheme, where the amount of avoided mineral N, P and K equalled the quantity of elements provided by the sediments.

2.4.4. Life Cycle Inventory (LCI)

The inventory stage covered the collection of all input data to describe the material and energy flows on the selected system. The data was collected by combining laboratory analyses for sediment characterisation, site-specific data (primary data) and background data (secondary data). Table 1 summarises the most important data used on the system and its source. The employed secondary data was taken from the EASETECH software (developed by the Technical University of Denmark) and included emission factors for the truck used for transportation (S1.1 and S.2); use of sediments on land (S2.2); fertiliser production and use (S2.3); construction and operation of the landfill (S1.2); biogas generation (S1.3); and treated and untreated leachate discharge (S1.4a-b).

Table 1. Input data collected on the life cycle inventory.

Data	Value	Involved Scenario	Source
Distance transportation	20 km	S1, S2	Primary data
Type of trucks	20–26 tonnes, EURO 5	S1, S2	Primary data
Type of precipitation	Moderate (500–1200 mm year^{-1})	S1, S2	Primary data
Leaching collection and treatment facility	Collection: 99.9% (first 80 years) and 20% (last 20 years of simulation)	S1	Assumption
Leaching treatment	Primary sedimentation + biological N removal + incineration sludge	S1	Assumption
Energy production with biogas	No existence of energy production	S1	Primary data
Type of soil	Sandy loam	S2	Assumption
Crop rotation	High	S2	Assumption
Spread of sediments	Use of tractor (combustion of 1 L of diesel)	S2	Assumption

2.4.5. Life Cycle Inventory Assessment (LCIA)

The LCIA was performed using the EASETECH software with the methodology ReCiPe V1.11 Hierarchies Europe. The method is well-established and widely applied for LCA and includes several impact categories that are not of interest for this study. A mid-point methodology was followed, and the impact categories shown in this study were selected based on consultation with the manager and experts of the LIFE SURE project. The categories were selected based on the importance of the project and the relevance of the selected scenarios. Table 2 shows the impact categories selected for this study and their corresponding units. Results on Section 3 are presented on the specific unit for each category in a normalised format (using normalised factors provided by the software EASETECH).

Table 2. Selected impact categories for the life cycle inventory assessment in the study.

Category	Units
Global warming potential (GWP)	kg CO_2 eq.*
Freshwater eutrophication (FWE)	kg P eq.
Marine water eutrophication (MWE)	kg N eq.
Human toxicity (HT)	kg 1,4-DB eq.
Terrestrial ecotoxicity (TT)	kg 1,4-DB eq.
Freshwater ecotoxicity (FT)	kg 1,4-DB eq.
Marine water ecotoxicity (MT)	kg 1,4-DB eq.
Fossil depletion (FD)	kg oil eq.

*eq.: Equivalent, DB: Dichlorobenzene.

2.5. Sensitivity Analysis (Perturbation Analysis)

The results from the LCA can vary according to the variation of input data, possibly carrying substantial changes in the impacts caused by the scenarios. A sensitivity analysis was conducted to determine sensitive inputs and whether the assumptions used could highly impact the model results. A sensitivity ratio (SR) was calculated using Equation (1), which considers the relative change in the model result over the relative change in a parameter.

$$\text{Sensitivity ratio (SR)} = \frac{\frac{\Delta\text{result}}{\text{initial result}}}{\frac{\Delta\text{parameter}}{\text{initial parameter}}} \quad (1)$$

Eight variables (Cd, Pb, Zn, P, N, C, dry matter (DM) and transportation distance) were changed for the landfilling and soil conditioning scenarios, respectively. The variables were reduced by 10%. These variables were selected since they were expected to be influential in the impact categories selected in this study.

2.6. Cost Calculation

The economic evaluation was carried out for the same steps in both scenarios of the LCA under the same system boundary. The aim was to determine the cost of each handling strategy to assess the economic feasibility of landfilling the sediments or using them in soil conditioning. The costs for each process of the scenarios were taken from the local prices in Kalmar, Sweden.

3. Results and Discussion

3.1. Characterisation of the Sediments

The characterisation of sediments from Malmfjärden is shown in Table 3. The material presented high contents of nutrients (N, P and K) and the presence of micronutrients such as Zn, Fe, Mg, Mn, Ca and Na. Furthermore, the material presented a sub-acid pH and was highly organic, according to SS-EN ISO 14688e2:2018 [41]. Regarding metals/metalloids, Cd, Pb, As and Zn overpassed the threshold values allowed for agricultural soil. The limits given by the Swedish guideline [42] provide maximum permissible concentrations for less sensitive uses and more sensitive uses for soils. The high content of nutrients suggested a good potential for the material's use as a soil conditioner. However, the presence of toxic metals could pose a threat to the soil and human health if edible crops are harvested [5].

Table 3. Characterisation of dredged sediments from Malmfjärden Bay. In mg kg^{-1} DM (mean ± SD, n = 6).

Parameter	Sediment	Less Sensitive Limit	More Sensitive Limit
Solid content (%)	27.8 ± 3.5	-	-
LOI (%)	27.6 ± 11.7	-	-
TOC (%)	8.65 ± 0.38	-	-
pH (-)	5.30 ± 0.64	-	-
Ammonium	1433 ± 175	-	-
Cl	10,367 ± 3728	-	-
S	14,833 ± 4750	-	-
Total N	11,167 ± 1169	-	-
Total P	1317 ± 75	-	-
As	12.3 ± 2.63 **	10	25
Ba	74.3 ± 26.9	200	300
Pb	79.8 ± 9.2 **	50	400
Cd	1.44 ± 0.45 **	0.8	12
Co	10.2 ± 0.7	15	-
Cu	66.2 ± 2.6	80	200
Cr	39.5 ± 6.0	80	150
Mo	1.67 ± 0.06	40	100
Ni	29.0 ± 1.7	100	200
Zn	220 ± 36 *	250	500
V	63.7 ± 6.7	100	-
Al	29,000 ± 3605	-	-
Fe	32,333 ± 21,862	-	-
K	8117 ± 3190	-	-
Mg	8333 ± 750	-	-
Mn	330 ± 22	-	-
Ca	5650 ± 1470	-	-
Na	7666 ± 1039	-	-
Sum PAH-L	0.07 ± 0.02	3	15
Sum PAH-M	0.84 ± 0.08	3.5	20
Sum PAH-H	1.06 ± 0.26 **	1	10
Aliphatic C5-8	12.00 ± 0	25	150
Aliphatic C8-10	16.25 ± 7.50	25	120
Aliphatic C10-12	8.75 ± 2.50	100	500
Aliphatic C12-16	200 ± 37 **	100	500
Aliphatic C16-35	67.75 ± 34.94	100	1000
Aromatic C8-10	0.85 ± 0.10	10	50
Aromatic C10-16	1.73 ± 0.55	3	15
Aromatic C16-35	0.88 ± 0.25	10	30
Sum PCB 7	0.0078 ± 0.002 **	0.008	0.2
Sum BTEX	0.75 ± 0.50	-	-

* Values below but close to the more sensitive limits for [42]. ** Values overpassing the more sensitive limits for [42]. DM: Dry matter; TOC: Total organic carbon, LOI: Loss on ignition, SEPA: Swedish Environmental Protection Agency.

3.2. Environmental Impacts

The environmental impacts caused in each scenario by different activities are provided in Table 4.

Scenario S1—Landfilling: Landfilling presented emissions mainly related to the production of biogas while operating the landfill and even after closure (S1.3), as expected due to the generation of biogas in landfills related to the degradation of organic material [43]. Moreover, nitrogen and phosphorous can lead to the eutrophication of receiving water bodies where N and P primarily affect marine and freshwater, respectively [44]. This scenario caused no impact related to freshwater eutrophication (due to the low content of P in the dredged sediments also being reflected in the low content on the leachate) and a slight impact related to marine eutrophication (due to the content of N in the leachate (S1.4)).

Table 4. Environmental impacts expected in two handling strategies of sediments dredged from Malmfjärden Bay (22 tonnes): landfilling (S1) and use in soil conditioning (S2).

Scenario—Activity	Global Warming Potential (kg CO_2 eq.*)	Freshwater Eutrophication (kg P eq.)	Marine Eutrophication (kg N eq.)	Human Toxicity (kg 1,4-DB eq.)	Terrestrial Ecotoxicity (kg 1,4-DB eq.)	Freshwater Ecotoxicity (kg 1,4-DB eq.)	Marine Ecotoxicity (kg 1,4-DB eq.)	Fossil Fuel Depletion (kg Fe eq.)
S1.1 Transportation	24.4	0	0	0.7	0	0	0	8.0
S1.2 Landfill construction + operation	118.9	0	0	3.2	0	0	0	33.6
S1.3a Leachate treatment	12.7	0	3.4	23.1	1.2	0.6	0.5	2.9
S1.3b Discharge of uncollected/untreated leachate	0	0	0.2	1.0	0	0.1	0	0
S1.4 Gas emissions	3074.3	0	0	4.9	0	0	0	0
Total S1	**3230.3**	**0**	**3.6**	**32.9**	**1.2**	**0.7**	**0.5**	**44.5**
S2.1 Transportation	24.4	0	0	0.7	0	0	0	8.0
S2.2 Use on land	1511.6	0	19.1	1718.5	4.7	0.5	0.3	14.0
S2.3 Avoided fertiliser	−1423.1 **	−0.4	−9.7	−3459.8	−0.7	−39.4	−2.5	−84.9
Total S2	**112.9**	**−0.4**	**9.4**	**−1740.6**	**4.0**	**−38.9**	**−2.2**	**−62.9**

* eq.: Equivalents. ** Negative value means environmental savings. DB: Dichlorobenzene.

Regarding toxicity, the major impact expected is associated with human toxicity, followed by terrestrial, freshwater and marine ecotoxicity, respectively. The toxicity impacts were mainly related to the discharge of treated leachate from the landfill (S1.4a), which could impact ecosystems and human health [45]. Additionally, human toxicity was also impacted by the discharges produced by the construction and operation of the landfill (S1.2) and the low volume of uncollected leachate that escaped from the treatment step (S.1.4b). The biogas emissions (S1.3) also affected human health, due in particular to the release of nitrogen oxides [46]. Similar results were reported by Pasciucco, *et al.* [20], who determined that the landfilling of sediments is related to negative impacts mainly related to the global warming and toxicity categories.

The landfilling scenario also caused impacts related to fossil depletion, and the main contributors were the landfill construction and operation phases (S1.2). The impacts were associated with the consumption of fuels for machinery. Similarly, the leachate treatment equipment also consumed fuels, negatively affecting this category. The transportation of the sediments to the landfill (S1.1) required the consumption of fossil fuels, adding more impacts to the category.

Scenario S2—Use for soil conditioning: Soil conditioning was associated with negative and positive impacts allocated in all the studied categories. First, using the material in agricultural fields (S2.2) requires machinery that produces gas emissions related to climate change. Similarly, the transportation of the material (S2.1) implies gas emissions produced by the trucks. Both activities negatively impacted the category of global warming. The processes that were related to the production and use of the avoided fertiliser represented savings for the category since the recognised gas emissions to produce the fertiliser [42,47] were excluded from the accounting. The impact produced while spreading and using the sediments in soils was higher than the savings, causing an overall negative impact on global warming.

Regarding eutrophication, the scenario included negative impacts related to the use of the material in soils (S2.2) and the possible leaching of N that could reach the marine ecosystems [48]. The avoidance of fertiliser (S2.3) caused positive impacts by avoiding possible nutrient discharges, causing a positive impact on freshwater and marine eutrophication. However, the overall score for this last category is negative since the impact caused by the application of the sediments is higher than the savings from not producing or applying mineral fertilisers.

Thirdly, the use of sediments in agricultural soils (S2.2) is associated with the possible leaching of contaminants [5]. In the present case study, the possible leaching of metals contributed to human toxicity. Similarly, the categories of terrestrial, freshwater and marine ecotoxicities were negatively impacted. The avoidance of mineral fertilisers caused positive impacts in the toxicity categories. The savings were mainly associated with avoiding the discharge of pollutants while producing and using fertilisers [42]. Consequently, all toxicity categories (besides marine ecotoxicity) had a positive impact on the scenario. Finally, S2 was associated with consuming fossil fuels during transportation (S2.1) and the use of machinery to spread the sediments (S2.2). However, avoiding the production and application of fertilisers had a higher positive impact, providing an overall positive score to this category.

Similar results were reported by Zhu, et al. [49]. The study also evaluated the impacts caused while using dredged sediments in soil conditioning. The results showed positive environmental impacts related to the avoidance of using fertiliser. The main negative consequences were related to the uncontrollable release of nutrients and metals into the soil. Therefore, the study recommended this option for unpolluted sediments to reduce the pollution risk.

3.3. Comparison of the Scenarios

The scenarios of landfilling (S1) and soil conditioning (S2) received overall scores of 1.6 and −6.0 Personal Equivalent units (PE), respectively. Figure 4 shows the impacts caused by each activity on scenarios S1 and S2. The results are illustrated in PE to allow for comparison among scenarios. The activities associated with higher negative impacts were biogas emission (S1.3) and the discharge of treated leachate (S1.4a) for landfilling and applying dredged sediments on soils (S2.2) for soil conditioning. It can be seen that the negative impacts generated by S1.4a on eutrophication and toxicity categories were fewer than the impacts caused by S2.2. The results are explained when considering that the landfill includes environmental protection measurements like the collection and treatment of the produced leachate. The action minimises the harmful discharges to the environment. Oppositely, when sediments are used in agricultural lands, nutrients and metals leach out directly to the soil, with the risk of reaching water bodies and negatively contributing to the mentioned categories.

However, avoiding fertiliser (S2.3) on S2 was one of the most important aspects since it showed the potential of dredged sediments to be used as a resource able to contribute to stopping the depletion of natural resources. The environmental impacts that were not caused while not producing and using fertilisers were higher than those caused when using dredged sediments for soil conditioning, showing a positive environmental score for the handling option.

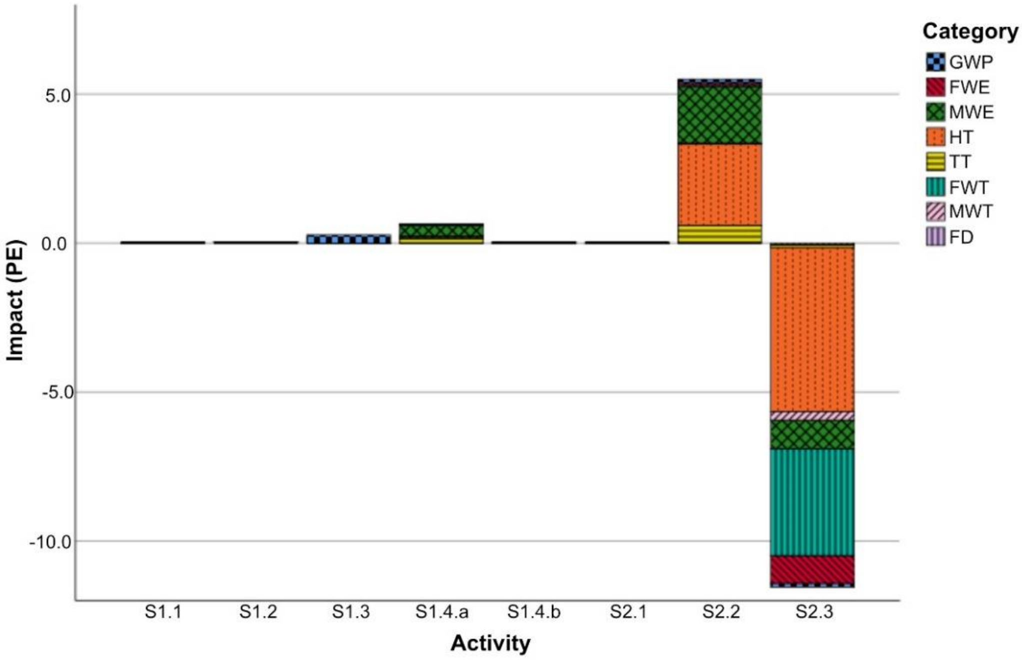

Figure 4. Normalised LCIA impacts associated with landfilling (S1) and soil conditioning (S2) of Malmfjärden dredged sediments. Abbreviations: GWP: Global warming potential; FEW: Freshwater eutrophication; MWE: Marine water eutrophication; HT: Human toxicity; TT: Terrestrial ecotoxicity; FWT: Freshwater ecotoxicity; MWT: Marine water ecotoxicity; FD: Fossil depletion and C&O: Construction and operation; S1.1: Transportation S1; S1.2: Construction and operation of landfill; S1.3: Emission of gases; S1.4.a: Discharge of treated leachate; S1.4.a: Discharge of untreated leachate; S2.1: Transportation S2; S2.2: Use of sediment on land and S2.3: Avoidance of fertiliser.

Regarding climate change, the landfill scenario had the highest impact by producing emissions of biogas during the operation of the facility. Applying dredged sediments in soils also generated gas emissions associated with the decomposition of organic matter from the material. However, the impacts related to global warming were fewer for S2 compared to S1. Results could be explained by the anaerobic conditions in the landfill, which promote the generation of biogas throughout the biochemical decomposition of the material [43]. Other activities in both scenarios did not produce considerable impacts related to the category.

Moreover, it was noticed that impacts produced during the transportation in both scenarios (S1.1 and S2.1), the construction and operation of the landfill (S1.2) and the discharge of uncollected leachate (S1.4.b) produced no considerable impacts when accounting for the overall scores of the scenarios. The results showed that if it is desired to minimise the impacts caused by the handling scenarios, the measurements shall focus on the emission of gases (S1.3) and treatment and discharge of leachate (S1.4.a) for S1. Moreover, attention shall be given to the spread and use of the sediments in soils (S2.2) for S2.

The LIFE SURE project aims to implement beneficial uses for dredged sediments. Therefore, considering the results of this LCA study, the recommendation is to employ the material in soil conditioning processes. Future studies could focus on the reduction of potential toxicity impacts, for example, by pre-treating the dredged sediments to reduce the metal content using technologies such as phytoremediation or chemical extraction [50]. The reduction of the availability of metals is also recommended, for example, by mixing the material with biochar [51] or with some forms of phosphates. Phosphoric acid (H_3PO_4), potassium phosphate monobasic (KH_2PO^4), hydroxyapatite, phosphate fertilisers and natural phosphate can immobilise Cd and Pb into more unavailable forms for biological systems via processes such as adsorption, dissolution and precipitation (Kede, et al. [52] Kede, et al. [53]. When the metals are less available, their leaching rates will be reduced, minimising the toxic impacts caused to the environment and human health.

The main limitation for both scenarios was the necessity to assume data. Changes in the input data are likely to affect the results of the model. With the soil conditioning scenario in particular, the distance to the land, type of soil and rotation rate for crops were assumed. Similarly, due to the heterogeneity of sediments, their quality can vary based on changes to the dredging area. Therefore, the sensitivity of the model is calculated in Section 3.4.

3.4. Sensitivity (Perturbation Analysis) and Analysis of Important Parameters

The results of the perturbation analysis according to the calculation of sensitivity ratios are shown in Figure 5. The tested parameters were chosen since they were elements related to the toxicity or eutrophication categories of impact, which were identified as crucial for this study. The initial contents of Cd, Zn, P, N, C and dry matter (DM) and the transportation distance varied -10% from the original values. Higher absolute SR values mean that the impact category is more sensitive to the parameter. It can be seen that the most influential parameter was P, followed by Cd, DM and C. The remaining parameters had a similar effect on the model. Similar results were reported by Zhou, Zhang, Li, Zhang and Wang [27], where the initial concentration of the handling material was one of the most influential parameters in an LCA focused on treatment and disposal strategies for dredged sediments.

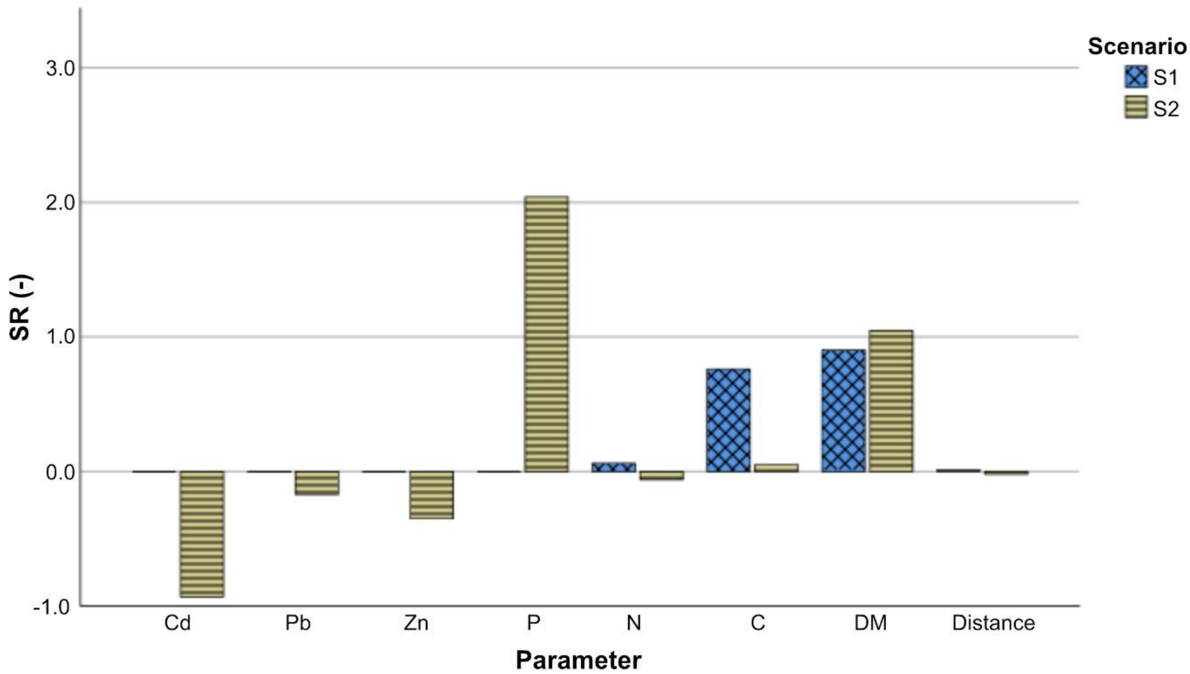

Figure 5. Sensitivity ratios (SR) calculated by reducing 10% of the selected parameters (Cd, Pb, Zn, P, N, C, Dry matter (DM) and transportation distance) in both scenarios (Landfilling: S1; Soil conditioning: S2). High absolute values of SR indicate parameters that caused more variation in the output model results.

According to Ferrans, Jani, Gao and Hogland [29], changes in the concentration of metals and nutrients are expected while dredging deeper layers of sediments. Moreover, the DM of the material can change depending on the time in the geobags (e.g., longer times can result in drier sediments). Therefore, due to the influence of the variables, it is important to consider a recalculation of the model output when the characterisation parameters are highly modified.

Figure S1 of the Supplementary Material shows the SR for the selected parameters on the different impact categories in both scenarios. It is shown that the variation in the content of Cd, Pb and Zn resulted in a reduction of the total impact caused in the soil conditioning scenario (S2). The only influential impact categories were human toxicity (HT) for the variation in the three parameters and terrestrial ecotoxicity for reducing the content of Zn. These results were expected since less content of pollutants decreased the impact in the categories. The reduction in the parameters presented no effect on the landfilling scenario (S1) since it was counted with a leachate treatment that decreases the environmental discharge.

The decrease in N caused considerably more positive impacts in the global warming potential category (GWP), associated with fewer N gas emissions into the environment for both scenarios. Similarly, the category of marine water eutrophication presented more positive impacts for soil conditioning (S2) due to the reduction of N. However, the fossil depletion (FD) category was associated with different effects for S2. The decrease in the element reduced the environmental savings associated with the avoidance of fertiliser (S2.3) since the sediments provided less N. The use of fossil fuels was similar during the transportation (S2.1) and use of sediments in soil (S2.2), resulting in a more negative score for the FD category in the scenario (S2).

Moreover, the reduction of P did not considerably effect the landfilling scenario. For the soil conditioning scenario, the decrease in the element caused fewer environmental savings related to the reduction in P applied from the sediments to the soil. The decrease in the compensation for avoiding fertilisers resulted in more negative scores for the categories of GWP, freshwater eutrophication (FEW), HT and terrestrial (TT), marine (MWT) and freshwater (FWT) ecotoxicities. On the other hand, regarding carbon, its reduction mainly influenced the GWP category, presenting more positive impacts on the category in both S1 and S2. In scenario S1, the change also produced a reduction in the HT impact category since fewer emissions with C were emitted.

The DM had an important effect since the content of elements was expressed on a dry basis. Therefore, decreasing the DM resulted in reducing the amount of all elements. For scenario S1, GWP and HT impact categories were more sensitive to changes in DM, presenting more positive impacts. For the soil conditioning scenario, the effects of reducing DM differed for the impact categories. First, the reduction of elements caused the reduction of the environmental savings related to avoiding fertiliser. Consequently, FEW, HT, FWT, MWT and FF impact categories were more negatively affected. Moreover, the decrease in elements due to the reduction of DM resulted in more positive impacts for the categories of GWP, MWE and TT.

The dredged sediment transportation distance to the facilities also influenced the model results. When this parameter is reduced, FD and GWP impact categories in both scenarios (S1 and S2) were less negative (since less fuel is employed). Bates, et al. [25] conducted an LCA about disposal methods for dredged materials. Their sensitivity analysis showed results similar to the present investigation since the transportation distance was an influential parameter of the model output.

3.5. Cost for Scenarios

The costs for each activity in both scenarios are reported in Table 5. Since the distance in each scenario was assumed to be 20 km, the total cost of transportation was the same in both cases (115 Euro). Kalmar has several neighbouring agricultural fields. Therefore, if the distance between the generation site and the use of the dredged material is longer than 20 km in S2, higher costs will be associated with transportation. Regarding S1, the cost for disposal of 1 kg of dredged sediments in the local landfill was approximately 0.07 Euro kg^{-1}, which represented a total cost of 1,540 Euro to handle 22 tonnes of dredged sediments.

Table 5. Costs associated with landfilling (S1) and soil conditioning (S2) Malmfjärden dredged sediments.

Scenario—Activity	Unit Cost (Euro/kg)	Total Cost * (Euro)
S1.1 Transportation	0.005	115
S1.2–1.4 Landfilling	0.07	1540
Total S1	-	**1655**
S2.1 Transportation	0.005	115
S2.2 Use on land	0.005	115
S2.3 Avoided fertiliser	−0.04	−780
Total S2	-	**−550**

* total cost for 22 tonnes.

The soil conditioning scenario S2 implied costs related to the spread of dredged sediments in the agricultural fields. Considering local costs, the activity costed around 0.005 Euro kg^{-1}. Moreover, the cost of the related avoided fertiliser was also assessed. Approximately 69 kg of nitrogen and 8 kg of phosphorous could be applied to soils considering the functional unit. In the local market, a 21N:4P:7K commercial fertiliser costs around 2.4 Euro kg^{-1}. To add 69 kg of N, 325 kg of fertiliser must be applied. Therefore, the avoided cost was calculated as approximately −780 Euro. Considering the cost and savings of S2, the total cost of the scenario was −550 Euro, showing positive economic impacts. The economic results from the study affirm the recommendation to implement the soil conditioning scenarios since they could generate savings for the final users of the dredged material.

A complete sustainable assessment requires the evaluation of economic, social and environmental aspects [54]. Therefore, it is recommended that further studies should focus on the social evaluation of both scenarios. Potential aspects to include are public awareness, social acceptance or job creation for each scenario.

4. Conclusions

Malmfjärden Bay in Kalmar, southern Sweden, was diagnosed as excessively shallow, with high contents of nutrients in the sediment. The EU LIFE SURE project aimed to dredge the bay by using more sustainable dredging machinery. One of the main targets of the project was to employ the dredged sediments for beneficial uses to contribute to the implementation of a more circular economy in the region. The present study aimed to assess the potential environmental impacts that could be caused while landfilling the sediments (scenario S1) and using the material in soil conditioning projects (scenario S2), followed by estimating the cost related to each scenario. The impacts produced by the transportation of already dried dredged material to the site for soil conditioning or a disposal site were included in the assessment.

Results showed that the soil conditioning scenario (S2) produced net environmental and economic savings due to the usage of the nutrients from the sediments, which led to a reduction in the production and consumption of fertilisers. Therefore, it is recommended to implement this approach for the handling of sediments considering the aim of the LIFE SURE project. The risk of realising metals and nutrients (affecting eutrophication and toxicity) must always be considered to avoid negative impacts on very sensitive ecosystems.

The landfilling scenario S1 presented only negative impacts. However, they were minimised since the facility (sanitary landfill) accounted for environmental protection measurements. The emission of global warming gases from the landfill operation was the main impact caused by scenario S1. Even though the facility accounted for leachate collection and treatment, the discharge of uncollected and treated leachate slightly contributed to the toxicity and eutrophication impact categories. The S1 scenario was regarded as the less preferable option since it lacks the recovery of valuable compounds from the sediments.

The beneficial use of dredged sediments is a potential path to avoid the disposal of the material in landfills and to find new sustainable sources of secondary raw materials, helping to stop the depletion of natural resources in a circular economic approach. However, the implementation is challenging since it involves technical, economic, environmental and social issues. The assessment of environmental impacts is seldom implemented. Since dredged sediments are also associated with potentially negative impacts to the environment and human health, the inclusion of LCA studies for the selection of the most sustainable sediment destinations is highly encouraged.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su142013139/s1, Figure S1: Sensitivity ratios (SR) calculated by reducing −10% of selected parameters (Cd, Pb, Zn, P, N, C, Dry matter (DM) and transportation distance) for both scenarios (landfilling: S1; Soil conditioning: S2) in each impact category. High absolute values of SR indicate parameters that caused more variation in the output-model results.

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Abbreviations

DM: Dry matter, ICP-AES: Inductively coupled plasma atomic emission spectroscopy, EU: European Union, FD: Fossil depletion, FWE: Freshwater eutrophication, FT: Freshwater ecotoxicity, GC−MS: Gas chromatography−mass spectrometry, GWP: Global warming potential, HT: Human toxicity, LCA: Life cycle assessment, LCI: Life cycle inventory, LCIA: Life cycle inventory assessment, MWE: Marine water eutrophication, ME: Marine water ecotoxicity, PE: Personal equivalent, S1: Landfilling scenario, S2: Soil conditioning scenario, SR: Sensitivity ratio, TT: Terrestrial ecotoxicity, TOC: Total organic carbon.

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