



# Beneficial use of sediments, tools, pilot sites and measuring techniques developed and used within seven European Union INTERREG projects

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## Abstract

**Purpose** The EU Water Framework Directive (European Union Off J Eur Comm 2000) and EU Waste Framework Directive (European Union Off J Euro Union 2008) impacted the Beneficial Use (BU) of sediments in Europe. INTERREG has supported initiatives to change the perception that sediments are a waste. In this paper we provide an overview of tools, pilot sites and measuring techniques developed and used for the BU of sediments within seven European Union INTERREG projects. We illustrate the lessons learned regarding barriers and enablers for BU of sediments.

**Materials and methods** BU of sediments is a combination of factors. The following aspects are considered. The sediment must be suitable for use and be in engineering compliance. The sediment must also need to meet the end of waste criteria, as well as to be in environmental compliance. To check in the field if engineering and environmental compliance is feasible, on-site analyses and decision support tools are needed. When BU use is possible, there must be a benefit, either in an added socio-economic value or in ecosystem services. To define benefits the impact of Business as Usual (BAU) should also be expressed. Stakeholder perception and spatial restraints determine areas for BU of sediments with spatial consensus.

**Results and discussion** The pilots and case studies described in this paper are examples of different applications of BU of sediments in northwest Europe. The tools, equipment, pilot tests and on-site monitoring techniques developed by the identified INTERREG projects are useful as BU enablers, for both citizens (an enabler is what is in it for me versus a barrier like residents opposing to proposed developments in their local area or the Not In My Back Yard (NIMBY) principle), and for regulators (what are the risks versus benefits as compared to BAU).

**Conclusions** The main barriers for beneficial use of sediments are the social acceptance when sediments are used on land (often seen as waste disposal) and the extra direct cost versus the cost for disposal, while indirect benefits such as the potential for nature development, the impact on Gross Domestic Product (GDP) or more locally on the extra jobs created, are generally not considered. Also, the impact of BAU is often not explicitly considered.

**Keywords** Beneficial use · Circular economy · Sediments · Dredging · Enablers · Barriers · Pilot projects · Mineral resource

## Abbreviations:

ADCP Acoustic Doppler Current Profiler  
BAU Business As Usual

BRO Beneficial Reuse Option  
BU Beneficial Use  
CBS Statistics Netherlands  
CEAP Circular Economy Action Plan  
CEDA Central Dredging Association

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EC DG-Research	European Commission Directorate-General for Research
EU	European Union
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GIS	Geographic Information System
INTERREG	European Territorial Cooperation
NUTS	Nomenclature of territorial units for statistics
OSPAR	the mechanism by which 15 Governments & the EU cooperate to protect the marine environment of the North-East Atlantic. Named from the original Oslo and Paris Conventions ("OS" for Oslo and "PAR" for Paris)
PIANC	Permanent International Association of Navigation Congresses
RTD	Research and Technological Development
SedNet	European Sediment Network
SIOT	Symmetric Input-Output Tables
WFD-2000	Water Framework Directive
WFD-2008	Waste Framework Directive

## 1 Introduction

Dredging is vital to social and economic development. In particular, dredging is vital to the construction and the maintenance of much of the water transport infrastructure upon which our economic prosperity and social well-being depends. Sediments are a valuable resource, not only as a substitute for extraction of minerals, but also to compensate for erosion or subsidence, to fertilize land or to help develop habitats such as wetlands. Hence the term ‘Beneficial Use of sediments’, in connection with the concepts of “Building with Nature” (Europe) or “Engineering with Nature” (USA). Sediments can be contaminated, and maintaining a sustainable sediment budget on a river catchment scale can be a challenge. The Water Framework Directive, introduced in 2000 (European Union 2000), strives for a good chemical and ecological status of water bodies. Sediments play a role in reaching this status. To address the challenges of contaminated sediments SedNet was set up in 2002 and funded by the EC DG-Research effort under the 5th RTD Framework Program. Scientific, policy and regulatory aspects of contaminated sediments and dredged materials were addressed by SedNet in the period between 2002 and 2005. This resulted in policy recommendations and guidance documents which have been disseminated to the EU sediment community and practitioners. Brils (2020) published on the progress with regard to the inclusion of sediment in European River Basin Management Plans

(RBMPs), reflecting that already in 2004 SedNet published the booklet on Contaminated Sediments in European River Basins (Salomons and Brils 2004), but that at that time the window to influence policy to include (contaminated) sediment management was missed.

The introduction of the EU Waste Framework Directive (European Union 2008) changed the landscape, in that dredged sediments under this framework are considered a waste. Water and sediment managers had to find new ways to maintain waterways and find beneficial use of sediments applications. To translate this knowledge, as developed by SedNet, to sediment applications beneficial for EU citizens, SedNet’s insights were used to set up pilot projects within INTERREG. INTERREG is part of the European Union’s Cohesion Policy and has as an objective to enhance the institutional capacity of public administrations, to resolve legal and administrative obstacles in border regions, to promote sustainable democracy and to strengthen mutual trust among citizens. In this paper, tools developed within seven INTERREG projects in northwest Europe are presented. The use of these tools is illustrated by their application on pilot sites. The seven INTERREG programs are (in alphabetic order): CEAMaS, GeDSeT, Smart Sediment, Sullied Sediments, SURICATES, USAR and VALSE. These seven INTERREG projects were carried out between 2008 and 2023, spanning the timeframe from the introduction of the EU Waste Framework Directive (European Union 2008) up to (but not taking into account) the EU Soil Monitoring Law (2023). In this paper we look back and forward to what enables the beneficial use of sediments as a resource and what are the barriers for implementation. In the European part of the Atlantic (OSPAR) 110 to 150 million (M) tonnes (t) of marine sediments are dredged and aquatically placed on the seafloor bottom on a yearly basis (period 2008 – 2020) (Cronin et al. 2023). The amount of sediment classified as beneficially used in this period varied between 5 and ~50 M t. The reported dredged and aquatically placed volume for the Baltic Sea is highly variable and partly uncertain between the years. In the period 2013 – 2019 the reported volume varied between 7 and 23 M t (HELCOM 2019), with a beneficial use of 6.6 M t in 2019 and 8.6 M t in 2018. The reported total volume of dredged material in Europe of 200 M m<sup>3</sup>, or 80 M t, in 2004 (Bortone et al. 2004) has roughly doubled to 160 M t in 2023.

Over the past 15 years the evaluation criteria for the application of sediments as a resource has changed partly due to the introduction of the European Union Directives in 2000 (Water Framework) and 2008 (Waste Framework) but also, the social economic drivers have changed. Nowadays there is a need for a broad stakeholder engagement. Both direct and indirect costs and benefits must be considered. There is a need to reduce greenhouse gas (GHG) emissions from land use and hence sediment handling. The EU

Green Deal (European Commission 2019), resulting in a circular economy action plan (CEAP 2020), has changed the view on the beneficial use of sediments as a resource in a positive way (sediments can save on the use of primary resources like sand). SedNet has a Working Group on Sediments in the Circular Economy, with members participating in the cited INTERREG projects. SedNet members also participate in the CEDA workgroup on Beneficial use (CEDA 2019a, b, c) and in the PIANC (2023) workgroup on beneficial sediment use.

To evaluate the broader goals of beneficial use of sediments all seven INTERREG projects have conducted pilots on the application of (contaminated) sediments and developed and applied tools based on geographical constraints and opportunities (CEAMAS, SURICATES), supply and demand models (GedSeT, USAR, VALSE), economic and social economic modelling (CEAMAS, GedSeT, SURICATES), clean up or immobilization of contaminants in sediments (CEAMaS, GeDSeT, Smart Sediment, Sullied Sediments, SURICATES, USAR, VALSE), engineering compliance (GeDSeT, Sullied Sediments, USAR, SURICATES), environmental monitoring and impact assessment (GedSeT, Smart Sediment, SURICATES) and GHG emissions (SURICATES). While the projects are conducted in northwest Europe the tools can also be applied in other parts of Europe or worldwide. In this paper we illustrate the background to some of these models and the lessons learned when it comes to the beneficial use of sediments, expressed as enablers and barriers (Lemiere et al. 2023).

## 2 Materials and methods

The INTERREG projects identified have developed and used multiple tools, compliancy tests and on-site analyses for the evaluation and outcomes of beneficial use options for sediments on pilot sites. In this paper we describe a selection of those tools and how they help to evaluate the beneficial use of sediments.

### 2.1 Beneficial use of sediments evaluated with PGIS

#### 2.1.1 Description

For the CEAMaS project Masson et al. (2015) developed a GIS model based on stakeholder (participants) interviews (hence the name PGIS). This model was refined for the SURICATES project. The stakeholder could indicate their perception of benefits and drawbacks of sediment use based on a questionnaire. The questionnaire addressed topics such as economic benefits, perceived job creation within the region and concerns for safety (like flooding, but also the presence of contaminants). The questionnaires were

translated to local enablers (factors stimulating the beneficial use of sediments) and barriers (factors inhibiting or restraining the beneficial use of sediments) (PIANC 2023). It is based on the notion of positive or negative externality and is close to the hedonic prices' method used in environmental economy (ESRI 2008). The value of the constraint is a decision cost that allows to accept or decline a spatialized scenario issued from the combination of the four types of constraints available, possibly weighted by the decision maker. This translation of the questionnaire information in a GIS model is known as spatial constraints' modeling in a raster mode and uses spatial analysis tool to calculate distances as a proxy of Not In My BackYard (NIMBY). This can be used as a basis for a GIS based Decision Support System (DSS).

#### 2.1.2 Application

The GIS based model was used for the Nord-Pas-de-Calais region of France (Masson et al. 2015). The outcome of local stakeholder questionnaires was combined with potential constraints (or parameters) classified in seven themes. Inclusion of areas of sediment resources and the economic transport distance for dredged material results in multiple GIS map layers. Combined these layers yield a map with spatial consensus on the beneficial use of sediments.

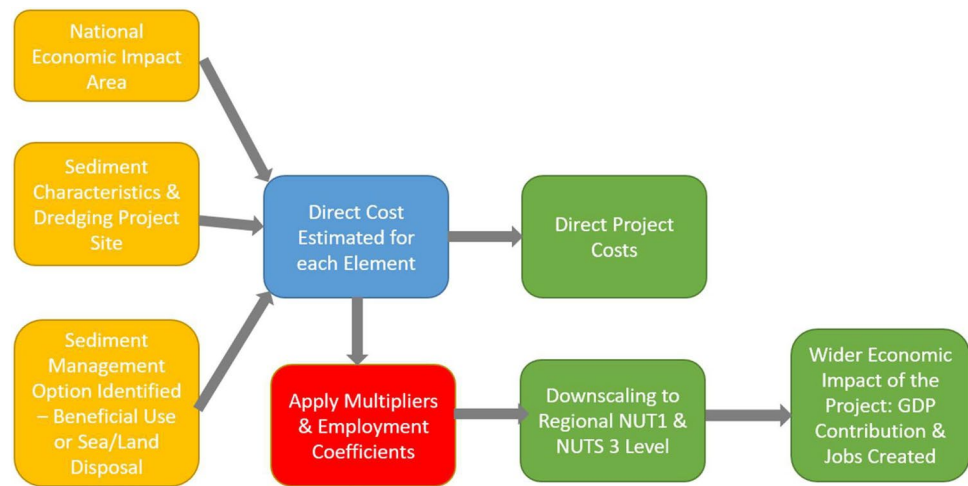
## 2.2 Economic and social economic modelling

### 2.2.1 Description

For the SURICATES project Harrington et al. (2022) developed an economic analysis and evaluation of sediment management projects model, derived from input–output analysis of an economic activity (Leontief 1951); the model is known as SedEcon. It calculates the impact on the Gross Domestic Product (GDP) and employment created. Figure 1 presents the general economic modelling framework developed and the overall approach applied for dredged sediments. It involves identification of the National Economic Impact Area (e.g. a country), identification of the dredging site and its sediment characteristics, preliminary selection of the potentially feasible sediment management options and development of the full logistical chain of project activity.

SedEcon uses Type I and II output multipliers and employment coefficients downscaled to EU Nomenclature of Territorial Units for Statistics (NUTS) Level 3 for the socio-economic analyses of regions. The multipliers are derived from Symmetric Input–Output (SIOT) tables, where the outputs of one industry sector correspond to the inputs of another industry (Leontief 1951). These input–output models generate a multiplier index that measures the total effect of an increase in investment on employment or income.

**Fig. 1** The economic analysis and evaluation of sediment management project modelling framework (from: Harrington et al. 2022)



There are three types of multiplier effect: direct, indirect and induced. Direct effects refer to the impact on economic activity of the industry/development. Indirect effects refer to the impact arising from upstream or inter-sectoral linkages, such as the income or jobs accruing to suppliers. Induced effects are impacts arising from general household spending of those directly and indirectly employed by the industry/development.

### 2.2.2 Application

The Castletownbere Harbour Development project is located in County Cork on the southwest coast of Ireland. The scope of the project comprised an extension to an existing concrete wharf, dredging of a berthing pocket, construction of two breakwater structures and land reclamation as a quay extension, all works undertaken on the Irish Government-owned Dinish Island in Castletownbere Harbour. The total quantity of dredged material was 66,000 m<sup>3</sup>. The project required an additional 28,000 m<sup>3</sup> of rock to be imported from three nearby quarries, located distances of 10 to 120 km from the site. The overall project cost is estimated at €20 million.

SedEcon calculates the impact of this project on the GDP. SedEcon not only provides results for the direct, indirect and induced contributions to GDP, but also for the direct, indirect and induced number of jobs created.

## 2.3 Environmental benefits and trade-offs

### 2.3.1 Description

BROADSEAT stands for "Beneficial Reuse of any Dredged Sediment Environmental Assessment Tool" (Lord and Torrance 2021) and was developed within the SURICATES project. It is designed to analyze the environmental merits (and trade-offs) of a proposed or completed beneficial reuse/use

dredging project. It uses professional judgement to compare the Beneficial Reuse Option (BRO) to the Business as Usual (BAU) case. It scores this qualitatively, using the answers to a series of questions. There are 52 questions each relating to a single factor, split between the 10 categories of transport comparison, energy comparison, circular economy aspects, waste management aspects, waste regulation aspects, water environment, ecosystem services, biodiversity and conservation, socio-economic impacts, UN Sustainable Development Goals. These are arranged into four equally weighted groups (Energy, Waste, Environment, Societal). For each factor a default weighting is provided, which is multiplied by the binary score generated by the answer to each question to give a score for the performance on this factor, which is then summed across all questions to give an overall score, which is displayed graphically.

### 2.3.2 Application

BROADSEAT was applied to analyze the impacts of a range of different sediment management projects and techniques, including at a number of SURICATES pilot sites; sediment bioremediation at the Falkirk Pilot Site, Scotland; in-water sediment reallocation at the Port of Rotterdam pilot site, The Netherlands; breakwater construction and land reclamation at Port of Calais, France and wetland creation and dyke construction in Port of Fenit, Ireland. The dredged sediment volumes involved range from approximately 500 m<sup>3</sup> to 500,000 m<sup>3</sup>.

## 2.4 Engineering compliance for dewatering

### 2.4.1 Description

Engineering compliance depends on the application. Safhi (2023) published 'Valorization of Dredged Sediments as

Sustainable Construction Resources' on the engineering conditions versus the properties of sediments. IXSANE (a consulting company from France) developed a mobile and continuous granulometric classification and dehydration pilot to improve sediment reuse strategies. Mechanical processes are used to extract residual waste and gravels ( $> 2.5$  mm), to extract the sandy fraction ( $> 60$   $\mu\text{m}$ ), and to press the fine sediment fraction after flocculation treatment in a continuous process for dehydration (Fig. 2). Packed in three containers, this pilot unit demonstrated its capacity to deliver raw materials extracted from sediment for various engineering applications.

### 2.4.2 Application

A pilot application on dewatering example within the INTERREG project SURICATES is given by Debuigne et al. (2023). The dewatering equipment was designed for the Bowling regeneration works with Scottish sediment. However, due to COVID restrains most tests were conducted in two quarries in Pays de la Loire Region in France with quarries fines, completing an initial test operated with fluvial sediment in North of France. Polymer treatment associated with an innovative use of a continuous pressing system for water extraction increased the speed of onsite dehydration of fine fraction materials. The input requirement at the pilot site were; sediment need to have a high water content (sediments have to be easily pumped); the maximum input flow of this pilot equipment is  $50 \text{ m}^3 \text{ hour}^{-1}$ ; the maximum output flow for thin dehydrated fraction (silt and clay) is  $\pm 250 \text{ kg hour}^{-1}$  of dry matter.

## 2.5 Environmental compliance by total concentration and leaching test on sediments from five pilot sites

### 2.5.1 Description

Environmental assessments, including testing for the presence and leaching of contaminants are needed, both from the Waste Framework Directive (European Union 2008)

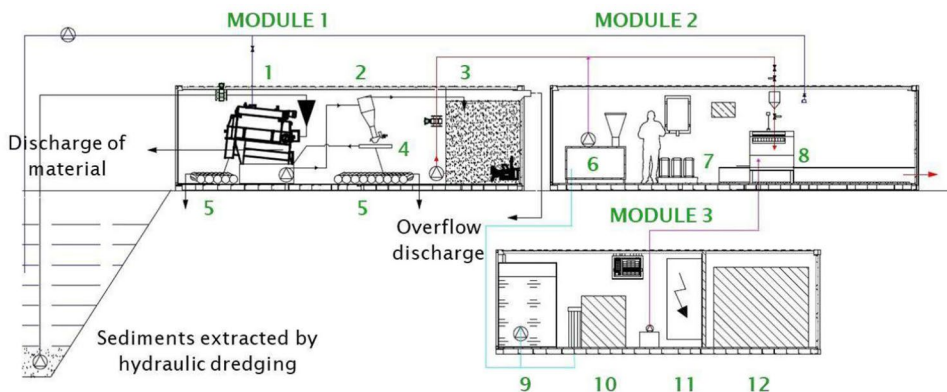
(end of waste status) and the Water Framework Directive (European Union 2000) (impact on the ground- and surface water quality). There are differences in the way these two Frameworks are implemented by the EU member states. These differences have an impact on the potential beneficial use of sediments for each EU member state. All EU member states have soil standards, but the contamination level at which a soil is deemed unfit for beneficial use differs. Some EU member states have standards based on leaching of building material. Leaching tests yields information on the risks of contamination for the environment. Leaching tests are also used to define the actual risk of contaminated sediments before deciding if a cleanup is needed. Leaching tests can be used for the Water Framework Directive, to evaluate if sediments can pose a risk for water quality.

### 2.5.2 Application

In the CEAMaS project, the impact of different soil and sediment standards between EU member states on the beneficial use of sediments were illustrated by testing sediments from five locations in France, Flanders, Ireland, and the Netherlands. The total sediment concentration of the Water Framework Directive priority substances (metals and organic contaminants), with the addition of country specific priority substances, was analyzed by a NEN-EN-ISO/IEC 17025 (2018) accredited laboratory. To be noted, only the Netherlands uses a soil standard based on a correction for the clay and organic matter content of the soil or sediment (Wijdeveld 2019). In addition, a series of leaching tests according to NEN 7343 (2006) (now NEN-EN-ISO 21268–2 (2019) were conducted. Sediment samples were provided by the partners of the CEAMaS project.

The total concentrations in each of the five samples were compared with the 2019 soil standards for Ireland, Flanders, France, Germany, and the Netherlands. If there were multiple tiers (lower and upper level) the upper tier was used to define if a sediment could be used beneficially. The principle 'one out – all out' was applied, if one contaminant exceeds

**Fig. 2** Granular classification and dehydration pilot (from: Lemiere et al. 2023)



the standard, the sediment is not deemed suitable for beneficial use. The leaching test results were compared with the national standards for leaching with a Liquid to Solid (L/S) ratio of 10 to 1.

## 2.6 Use of on-site analyses by pXRF as a decision support tool

### 2.6.1 Description

On site monitoring helps to identify potential hazards and evaluate local patterns in sediment or soil contaminant levels and groundwater pollution (monitoring in wells). On-site instruments provide immediate results and allow dynamic or adaptive sampling strategies, as well as allowing operational decisions in real time. Lemière et al. (2022) provides an extensive overview of analytical techniques on-site and in the lab that were used for the pilot sites in the GedSet and SURICATES projects. In this paper, the focus is on the Portable X-ray fluorescence (pXRF) for solids and on the multiparametric probe for water. pXRF can be used for a routine measurements for most of the major elements (Ca, Fe, K, Ti, Mn, and, often with lesser accuracy or higher deviation, Si, Al, P, S and Cl) and for many trace elements (often contaminants: Pb, Zn, Cu, As, Sb, Cr, V, etc.). Its analytical results are less precise than many recent laboratory techniques, but nevertheless sufficient for the discrimination of contaminated sediments. Multiparametric probes are field instruments comprising a pressure/depth profiler and several physicochemical sensors for water monitoring (temperature, EC (electric conductivity/salinity/TDS), pH, ORP (redox potential), dissolved oxygen).

### 2.6.2 Application

On site monitoring with pXRF was used for several case studies in the SURICATES, CEAMaS, VALSE and Ged-Set projects. Lemière et al. (2022) present three of them, the reallocation of dredged sediments in the waterway at Port of Rotterdam, the Netherlands; the canalside regeneration area at Bowling, Scotland UK, and Walloon Waterways Sediment Characterisation Surveys, Belgium. All sites were surveyed with pXRF, using grab samples for the waterways to collect 20 sediments from the upper 20 cm of the sediment at four different time intervals from before to 1 year after the sediment reallocation in Port of Rotterdam. For the Walloon Waterways 83 core sediment subsamples were dehydrated and analysed on board by pXRF. Results were available before moving the ship and could be used for selecting another sampling point in case anomalous concentrations were found. This sampling strategy is also called ASAP (Adaptive Sampling and Analyses Program). For the Bowling site (on land) an auger was used for sampling surface soils following an irregular grid pattern with points spaced approximately at 50–75 m intervals. For the Bowling site the nine groundwater wells were measured up to a depth of seven meters with the multiparametric probe, characterizing infiltration or seawater intrusion (Fig. 3).

## 2.7 Validation of the sediment balance with DTS and rare earth elements survey techniques

### 2.7.1 Description

Even large-scale beneficial use of sediments (500,000 m<sup>3</sup> of sediment) can be difficult to trace in a port like Rotterdam

**Fig. 3** On site monitoring of sediment chemical characteristics with a handheld XRF (left) and groundwater quality (right) by multiparametric probe at the Bowling site, Scotland, UK (from: Lemier et al. 2022)



(Fig. 4.) with a yearly dredged volume of  $\pm 10 \text{ M m}^3$  sediment (Kirichek 2022).

To quantify the sedimentation at the target pilot location in the Port of Rotterdam an optical cable with a Distributed Temperature Sensing (DTS) unit was used to determine the thermal capacity based on the sediment to water ratio. This can be used to determine the sedimentation/erosion rate and sediment density over time (during a tide) and hence the sediment balance at the target pilot site (the near field impact of reallocation).

For the far field evaluation (plus and minus 20 km from the reallocation site in the port) rare earth elements were used as a proxy for sediments origin and supply. They were analyzed in 20 grab core samples at four time periods, from  $T_0$  (before reallocation) to  $T_4$  (3 months after reallocation).  $T_1 - T_3$  were carried out during the 9 months reallocation period of 500,000  $\text{m}^3$  sediment. The reallocated sediments have a fluvial background (Rhine sediment), while the pilot site is dominated by the sedimentation of marine sediments. Due to an excess of Lanthanum (La) in Rhine sediment the ratio of La versus the other rare earth elements (Ce, Pr, Nd, Sm, Gd, Tb, Dy, Er, Tm, Yb and Lu) can be used to calculate the contribution of the fluvial Rhine sediments in different parts of the port.

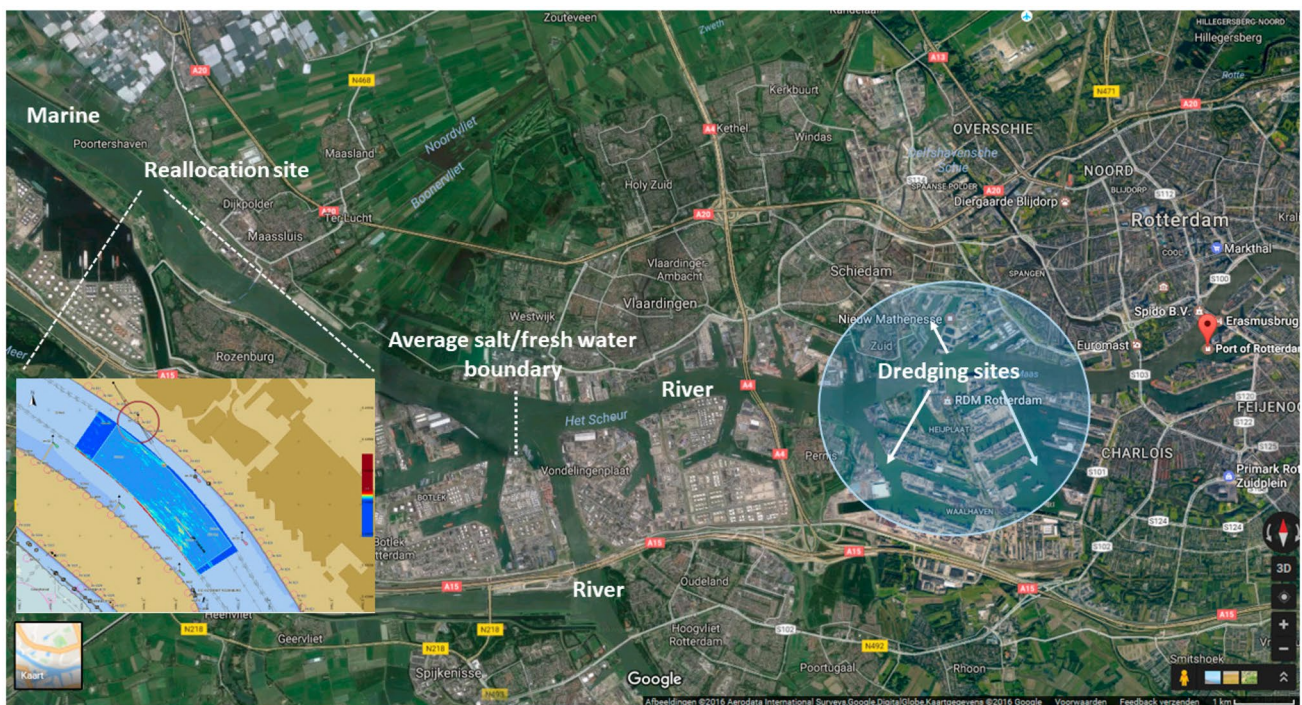
### 3 Results

#### 3.1 Tool: Beneficial use of sediments evaluated with GIS

Spatial consensus is a strategic area where stakeholders scenarios overlap according to their own decision's rule set. The spatial consensus area among stakeholders helps in reducing the number of potential locations to be analyzed for the beneficial use of sediments. The result for the North France region is plotted as a map with no spatial and spatial consensus (Fig. 5). This spatial DSS, or PGIS, for the North France region is useful as a tool to support the decision process among stakeholders.

#### 3.2 Economic and social economic modelling

The economic model was applied to the Castletownbere Harbour Development project (Harrington et al. 2022). The model estimated the direct cost of the dredging and quay extension and breakwaters (all the sediment management-related aspects of the project) at €6.49 M. The actual cost of these elements of the project was in the range from €7 to €8 M. The actual project created 35 to 40 FTE jobs with a



**Fig. 4** Port of Rotterdam, source location (dredging sites) and nourishment location (reallocation site), with the boundary of the tidal salt water intrusion (from: Lemier et al. 2022)

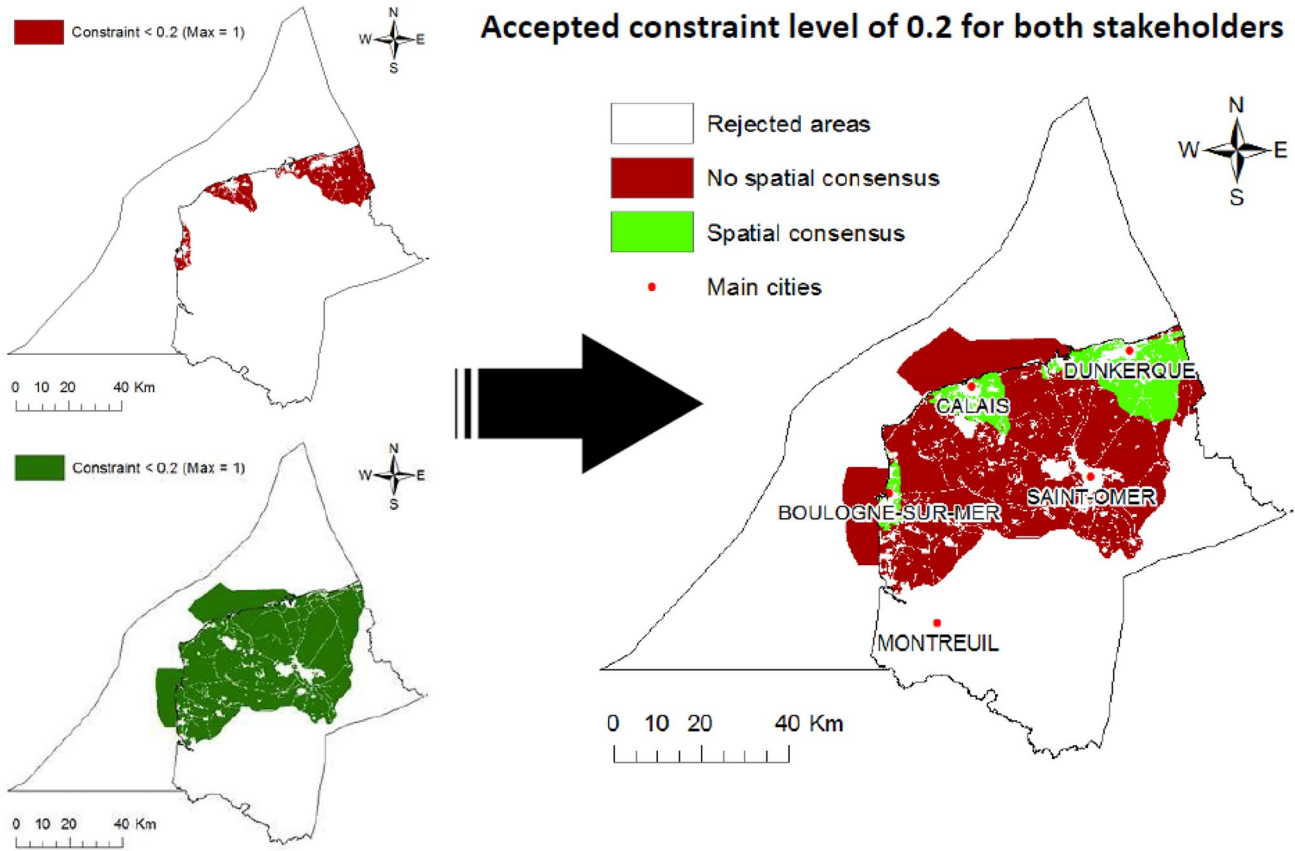


Fig. 5 GIS based model with stakeholder’s views on the benefits and drawbacks of sediment use (from: Masson et al 2015)

satisfactory model prediction of 40 FTE jobs. Indirect and induced contributions to GDP and employment created estimated from the model is presented indicating the substantial benefits accruing to the region from the project, such

valuable information is not generally available for these projects. Figure 6 presents the application of SedEcon for the dredging and land reclamation project at Castletownbere Harbour in the southwest of Ireland (Harrington et al. 2022).

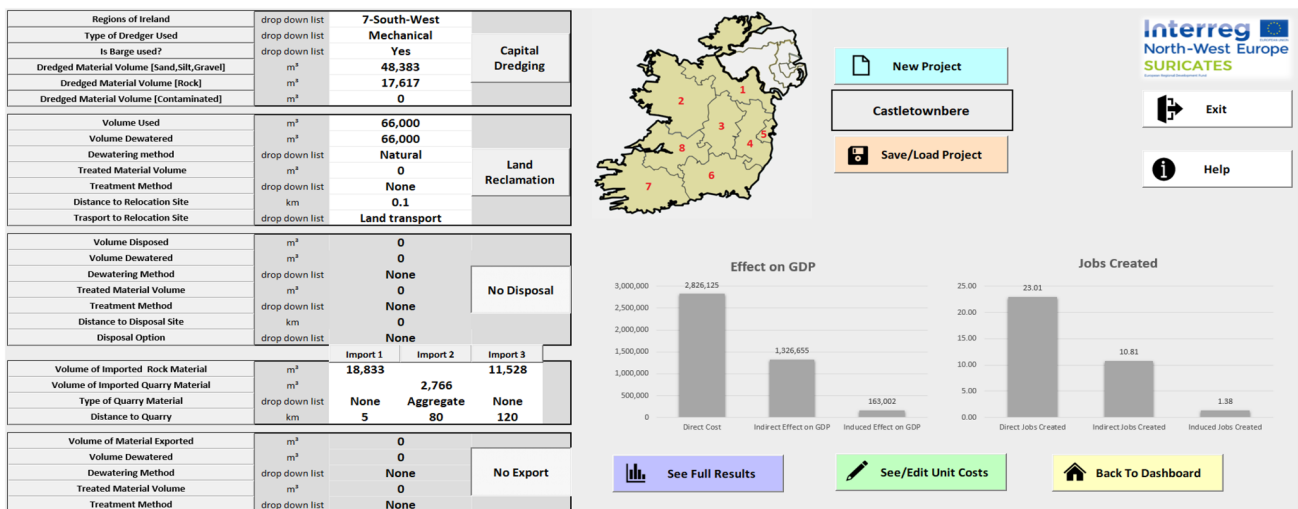


Fig. 6 The application of the economic model (SedEcon) for dredging and sediment management for the Castletownbere Harbour development in Ireland (from: Harrington et al. 2022)

### 3.3 Environmental benefits and trade-offs

The BROADSEAT tool balances beneficial use of sediments alternatives against their impact on Energy, Waste, Environment and Societal impacts. The example used here is for the Falkirk trial where clean dredged canal sediment was allowed to dewater naturally before being planted with grass seed. The results (Fig. 7) illustrate the possible trade-off between energy use and the waste, environmental and societal benefits of the BRO compared to the BAU, in this case natural dewatering and phyto-conditioning of sediment to make topsoil, rather than disposal to a landfill.

### 3.4 Engineering compliance for dewatering

The use of the equipment demonstrated added value for sediment management in complex dredging operations

	Default weightings	Your weightings
<b>Total scores (%)</b>	37	41
<b>Validity check</b>	Valid default weightings BRO score	Your valid BRO score
<b>Component scores</b>		
<b>ENERGY %</b>	-4	5
<b>WASTE %</b>	52	49
<b>ENVIRONMENT %</b>	32	50
<b>SOCIETAL %</b>	68	60
<b>ENERGY</b>		
<b>WASTE</b>		
<b>Environment</b>		
<b>SOCIETAL</b>		

Fig. 7 Output scores from BROADSEAT as applied to the Falkirk dewatering trial (from: Lord 2021)

for small to medium dredging campaigns. On site tests demonstrated the capacity to generate in less than 3 h raw materials which are easy to handle for beneficial reuse with 3 material flows extracted from sediments; gravel and material above 2.5 mm; sand and dehydrated fine fraction (50% of dry matters/50% of residual waters).

### 3.5 Environmental compliance for leaching test on sediments from five pilot sites

Wijdeveld (2019) illustrated for five sediments from pilot sites that in Ireland and France only two out of the five sediments can be beneficially used, while in Belgium (Flanders) and the Netherlands all five sediments were suitable for beneficial reuse (Table 1). Flanders and the Netherlands use leaching tests, while France and Ireland have total concentration standards for sediments.

### 3.6 Use of On-Site Analyses by pXRF as a Decision Support Tool

The results of the on-site pXRF and multiprobe measurements for the three pilot locations, supplemented with alternative in-site and near real time analyses, are published by Lemière et al. (2022). As an example, the main potential source of metal contamination for the regeneration area at Bowling (Fig. 8) is the forested area north of the river Clyde (Fig. 9).

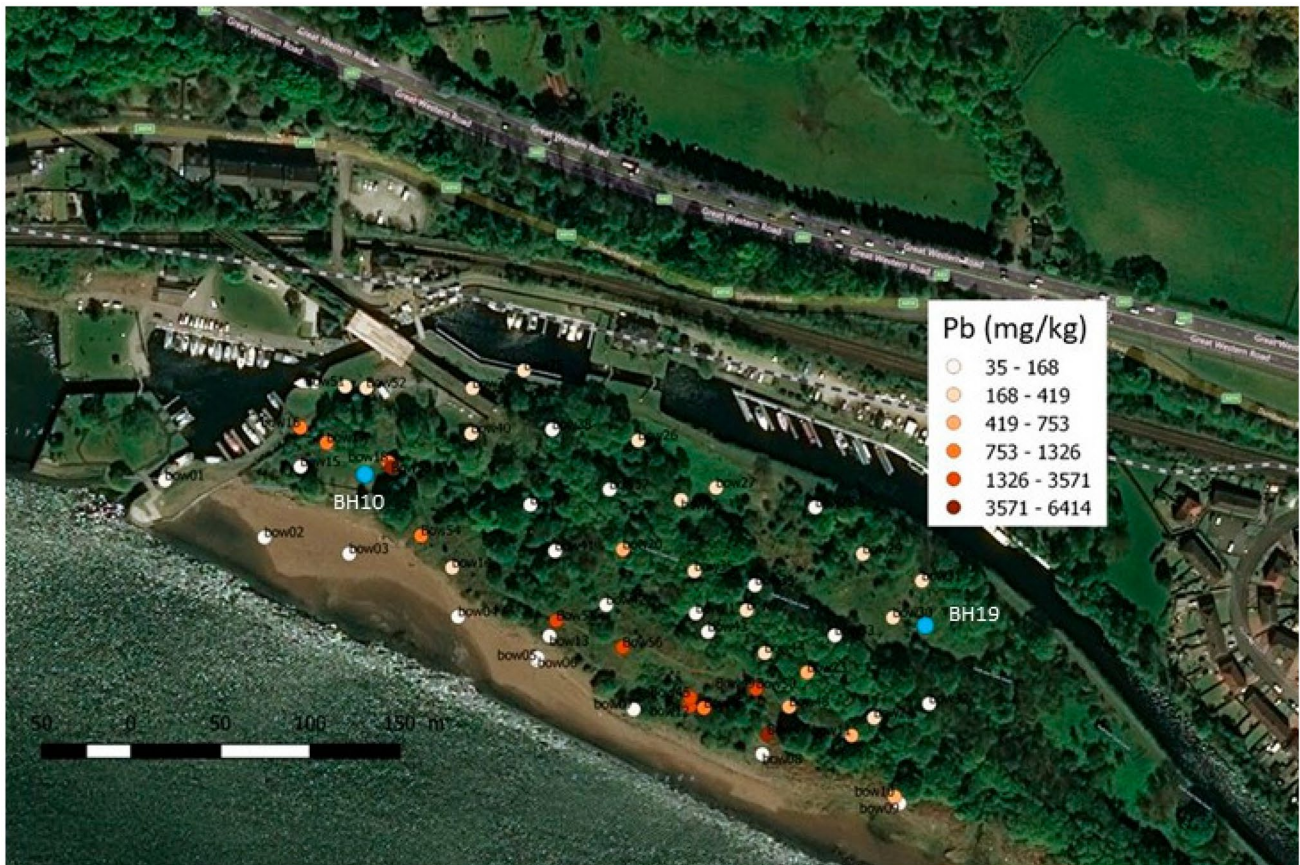
### 3.7 Validation of the sediment balance with DTS and rare earth elements survey techniques

The distribution of heat was translated to an erosion/sedimentation balance for the target pilot area during a period of one tide (13 h) (Wijdeveld 2021a) (Fig. 10). This was done in a period with a daily suppletion of 10,000 m<sup>3</sup> sediment (two times unloading of a 5,000 m<sup>3</sup> hopper dredger) at a distance of 20 m from the pilot area. However, the reallocation was in the main navigation channel at a depth of 16 m, while the pilot area was 5 m in depth. There was no sedimentation at the target pilot site (no near field effect).

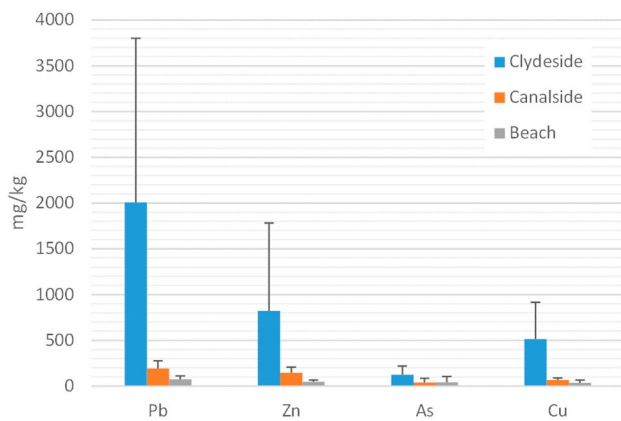
The far field (plus and minus 20 km) effects on sedimentation due to the reallocation of 500,000 m<sup>3</sup> sediment in the Port of Rotterdam were negligible (Wijdeveld 2021a). On average the increase in the sedimentation of Rhine sediment in the study area due to the reallocation is 0.2%, while on the riverbank next to the reallocation site (the constructed wetland) there is a decrease of 1.3% in the harbor sediment fraction. An overall evaluation of the impact of the reallocation of 500,000 m<sup>3</sup> sediment is given by Wijdeveld (2021b).

**Table 1** Evaluation of the metal concentration in five sediments according to four (Irish, Flemish, French and Dutch) upper limit sediment standards for use as building material, overall index based on the WFD-2000 “one out – all out” principle (from: Wijdeveld 2019)

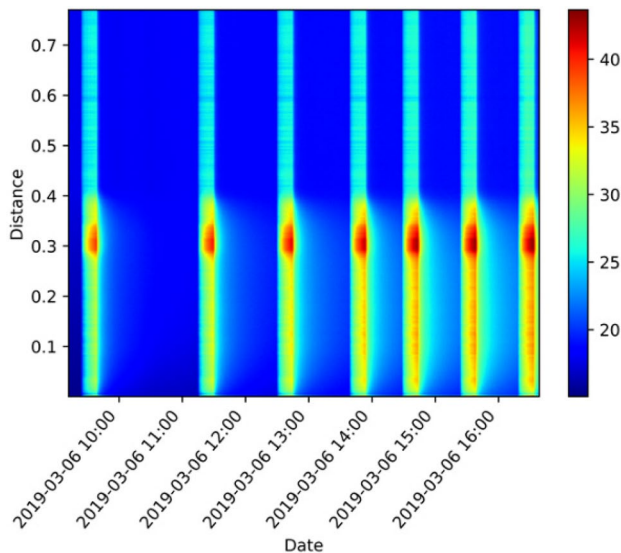
metals	Irish Upper level b					Flemish Secondary resource					French Level 2 (N2)					Dutch Bbk (class B)				
	Example 1	Example 2	Example 3	Example 4	Example 5	Example 1	Example 2	Example 3	Example 4	Example 5	Example 1	Example 2	Example 3	Example 4	Example 5	Example 1	Example 2	Example 3	Example 4	Example 5
Antimony																7%	7%	5%	9%	7%
Arsenic	25%	17%	18%	63%	42%	7%	5%	5%	18%	12%	35%	24%	25%	88%	59%	19%	10%	19%	43%	27%
Barium																4%	17%	4%	7%	5%
Cadmium	49%	14%	27%	151%	90%	21%	6%	11%	64%	38%	86%	24%	47%	265%	157%	17%	3%	16%	46%	24%
Chromium	81%	17%	25%	134%	96%	8%	2%	2%	13%	9%	54%	11%	17%	89%	64%	16%	3%	4%	27%	18%
Cobalt																21%	11%	9%	10%	15%
Copper	48%	36%	57%	69%	48%	14%	10%	17%	20%	14%	58%	43%	69%	85%	59%	25%	13%	44%	32%	20%
Lead	74%	35%	49%	57%	40%	13%	6%	9%	10%	7%	81%	38%	54%	62%	44%	26%	10%	23%	18%	12%
Molybdenum																				
Nickel	35%	46%	48%	57%	42%	8%	11%	12%	14%	10%	28%	37%	35%	46%	34%	1%	1%	1%	1%	0%
Selenium																5%	4%	4%	8%	5%
Tin																2%	2%	2%	4%	4%
Vanadium																0%	0%	0%	0%	0%
Zinc	194%	39%	53%	139%	92%	64%	13%	17%	46%	30%	144%	29%	39%	104%	69%	14%	3%	4%	19%	14%
<b>overall</b>	<b>194</b> %	<b>46</b> %	<b>57</b> %	<b>151</b> %	<b>96</b> %	<b>64</b> %	<b>13</b> %	<b>17</b> %	<b>46</b> %	<b>30</b> %	<b>144</b> %	<b>43</b> %	<b>69</b> %	<b>265</b> %	<b>157</b> %	<b>28</b> %	<b>17</b> %	<b>44</b> %	<b>46</b> %	<b>27</b> %



**Fig. 8** Lead (Pb) measurements by pXRF in soil at the canalside regeneration area at Bowling (from: Lemiere et al. 2022)



**Fig. 9** Comparison of the mean content in Pb, Zn, As and Cu for the three zones at the regeneration area at Bowling, Clydeside is the forested area north of the river Clyde, Canalside is the forested area south of the canal and Beach is the sandy zone along the river Clyde (from: Lemiere et al. 2022)



**Fig. 10** The distribution of temperature after heating the optical cable to 55 °C as function of depth (y axis – legend is in °C) and time (x-axis), heat in surface water is quickly dissipated (blue) while heat is ‘trapped’ in the sediment (red) (from: Wijdeveld 2021a)

## 4 Discussion

The volumes of dredged sediments in Europe (OSPAR and HELCOM region, only the marine sediments) have increased from roughly 80 M t in 2004 (Bortone et al. 2004) to 160 M t in 2023. Beneficial use of sediments has also increased, from unreported before 2013 (Cronin et al. 2023) to peaks up to 44% of the total dredged marine sediments. One uncertainty is the definition of the beneficial use of

sediments. Both OSPAR (Cronin et al. 2023) and HELCOM (2019) have defined beneficial use of sediments classification systems, the most common being beach nourishment and sediment recharge. Yet not all EU member states use the same definition of beneficial use of sediments. In some EU member states this notion of beneficial use is only just beginning to be mentioned by the regulator and legislation on what sediment quality can be accepted for beneficial use differs between EU member states. Beneficial use of sediments has been a priority in many INTERREG projects. The tools, equipment, tests and monitoring techniques developed within INTERREG projects over the past 15 years help to assess multiple criteria for the beneficial use of sediments. These tools provide insight in what PIANC (2023) calls ‘enablers and barriers of beneficial use of sediments’.

The key features for the viability of a beneficial use of sediments project often lies in social acceptance. Den Heijer (2023) illustrates this in a different context, the flood defence asset management. Flood defence management requires situational cooperation. Or in other words, bottlenecks in complex decisions for flood defence could not be solved by technical knowledge alone but needed a multi-actor setting with citizen participation. Technical feasibility or geotechnical compliance of natural sediments remains an important topic, as is illustrated by the paragraph on engineering compliance for dewatering. Studies by (Barciela-Rial 2019) and (Barciela-Rial et al. 2020) illustrate that by studying sediment properties and heterogeneity in relation to geotechnical important parameters like shear strength and consolidation natural sediments can be used as an alternative in civil engineering works like in dikes or as landfill material for new islands. But a recurrent topic in all seven INTERREG is that the need for social acceptance has increased and is of at least as much importance as overcoming geotechnical challenges with sediments. The PGIS tool helps reach spatial consensus among stakeholders and therefore helps in reducing the amount of potential locations to be analyzed for the beneficial use of sediments. Beneficial use of sediments has to provide benefits and economic gains. The SedEcon tool provides insight in the direct, indirect and induced benefits of a sediments project, including the impact on the local economy by promoting sediment application related job creation. To assess the balance between the relative costs and benefits of a Beneficial Reuse Option (BRO) versus the Business As Usual (BAU) case the tool BROADSEAT can be used. Another part of the challenge for beneficial use of sediments is to produce valuable resources out of sediments and/or replacing unrenovable resources. By valorisation of a dewatering installation for an INTERREG pilot site the engineering compliance was tested. By testing sediments from five EU member states against five national soil standards, including an assessment on

the leaching of contaminants, an overview was generated on the EU member states with relatively high barriers for beneficial use of sediments (strict sediment standards) and EU member states who focus on enabling beneficial use of sediments. This is accomplished by focusing on avoiding contamination of ground and surface water (leaching), allowing higher contaminant concentrations based on the absence of direct exposure to organisms or emissions to water. On-site measurements can help in the assessment of sediments. The use of pXRF equipment can help in setting up an Adaptive Sampling and Analyses Program (ASAP) to save on cost for a more detailed and costlier lab analyses, as well as to facilitate community communication by offering a access to real-time measurements. New techniques such as optical cables for temperature measurements in water and sediment and the use of rare earth elements as tracers will help to improve the insight in the sediment mass balance within a water body.

## 5 Conclusion

The main barriers for beneficial use of sediments are the social acceptance when sediments are used on land (often seen (perceived) as waste disposal) and the extra direct cost versus the cost for aquatic and/or Confined Disposal Facility (CDF) disposal, while indirect benefits like the potential for nature development, the impact on GDP (or more locally on the extra job creation) are generally not considered. Also, the impact of Business as Usual is often not explicitly considered. All tools, equipment, tests and on-site monitoring techniques developed by the identified INTERREG projects are useful as enablers, for both citizens (what is in it for me versus NIMBY) and for regulators (what are the risks versus benefits as compared to BAU).

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## Declarations

**Conflicts of interest** The authors have no financial or proprietary interests in any material discussed in this article.

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