Marine sediment re-use in the ports of North Western Europe

Toward a spatial decision support system for “Civil Engineering Application for Marine Sediments” (CEAMaS project)

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Abstract

This contribution aims at presenting a spatial decision support system, in a geographical information system and applied to the assessment and the feasibility of a potential reuse path for marine sediments.

Its objective is to compare different ways of adding value to sediment. A geographical information system allows a solution to be spatially analyzed, and was therefore chosen for our study. Then, in a geographical information system, a decision support system was developed and tested. This decision support system is based on a spatial dataset, which considers the places of dredging, the sites of treatment and adding-value, and the sites of reuse. Developments and results, funded by the CEAMaS Interreg IVB North Western Europe project, are presented in this contribution on which to build future analyses.

Keywords— Marine sediments, GIS, Management, Dredging, Decision support system.

I. INTRODUCTION

CEAMaS (Civil Engineering Application for Marine Sediments) is a transnational cooperation promoted through EU funding to encourage knowledge and consensus to raise new solutions of reuse of marine sediments applicable to all of Europe. In Europe, an average of 200 million cubic meters (cu.m) of sediments is dredged every year. The management of dredged sediments is an increasing issue for harbours and local authorities where there is a lack of raw materials for construction at which sediments could be used.

CEAMaS project is a North Western Europe (NWE) Interreg IVB project in which 8 expert partners bring together their contributions, experiences and know-how in order to strengthen the emergence of marine sediments re-use applications. CEAMaS is a European project to promote the beneficial re-use of marine sediments (or valorization) in civil engineering applications, in a sustainable, economical and socially acceptable manner.

Legislation for handling dredged material is complex and from a policy perspective, dredged material is dealt at the intersection of EU Water, EU Waste and EU Marine Strategy Framework directives. Procedures and contaminant thresholds to authorize dumping at sea, or in land management, considerably vary from one country to another, and no harmonized regulations exist at EU level.

NWE has a long history of marine commercial activity with many ports of primary international importance and huge infrastructure capacities. Many of these ports face serious sediment management issues as a consequence of their position and openness to coastal and estuarine sediment fluxes. In many cases ports act as sediment traps and the cost of sediment management is often a critical factor in respect of the ports economic sustainability. Maintaining advertised safe navigational depth is key to port operations; therefore extensive dredging operations are required and produce increasingly large amounts of material as the ports deepen their fairways and berths to accommodate larger modern vessels.

These factors are driving ports sediment management strategies, which must also take national and European regulations into account. These regulations, which are primarily geared towards protection of coastal and marine environments, apply to many aspects of dredging and govern
the fate of sedimentary materials dredged. Such regulatory constraints strongly influence the scope of potential sediment management options, especially for sediments that are less than pristine and may contain varying concentrations of a range of contaminants, which are typically associated with the finer (clay-silt) fractions. In many cases, where sediments fulfill European and National chemical and physical criteria, the most common beneficial solution is for dumping at sea in specific regulated areas. In other cases dumping at sea is precluded, especially when contaminant concentrations exceed permitted thresholds. In these circumstances, alternatives are required. They typically involve costly storage or remediation solutions.

The overall sediment management cost may however be offset in cases where beneficial re-use options are employed: for instance, through treatments that enable dredged sediment to be converted into an aggregate resource, or, with the potential to replace or supplement materials sourced from the traditional aggregate market. However, because of these additional processing, costs must be taken into account when matching the price of continental aggregates; the economic transport distance for dredged material is reduced. The maximum practical transport distance can be used to define a buffer zone within which beneficial use may be considered as a feasible option. Moreover this buffer area has to be spatially analysed in order to pinpoint the likely areas of interest for each potential reuse application. This issue has highlighted the need of developing a spatial decision support system within CEAMaS project.

Spatial Decision Support System (DSS) are increasingly recognized within the DSS research community [1], [2], [3], [4], [5], because of their broad applicability across a range of fields including, inter alia, planning, impact assessment, and environmental management [6], [7], [8], [9], [10], [11], [12], [13]. Specific applications have been developed and combine DSS and Geographical Information System (GIS) to create solutions using weighted sum methodology [2], [3], [10]. The validity and utility of these techniques are now well established in several fields [2], but not yet in the marine sediment management community.

This paper presents an innovative, on going work in a GIS based DSS to provide a range of end-users (port authorities, consultants, regulators, educators…) with customized layers of spatial information covering key aspects, pertinent to the beneficial re-use of marine sediments. This operational decision making tool forms a methodology that integrates a multi-stakeholders decision rule set, processing GIS layers and weighted sum calculations. This methodology is fully detailed in the following part.

II. BUILDING A SPATIAL DECISION SUPPORT SYSTEM UNDER GIS

For this study, a GIS methodology has been defined and adapted to Nord-Pas-de-Calais region of France (Fig. 1), depending on the available data.

This methodology is based on spatial constraints’ modeling in a raster mode (Fig. 2), and uses spatial analysis tool to calculate Euclidian distances [14] as a proxii of NIMBY (i.e. Not In My Back-Yard) / BAU (i.e. Business As Usual) qualitative assessment.

![Location map of the Ceamais French case study](Data source Eurostats 2014, BDTopo® IGN 2012).

A. Raster type-modelling

GIS offer two types of data representation: The vector mode is a discreet objects’ model where the information is available only for the existing objects; and the raster mode, which is a grid-like model that corresponds to a normalized spatial sampling following a user-defined spatial resolution [14], [15].

For this project, the choice of a raster-based modeling was dictated by modeling constraints, notably the fact that the elaboration of a spatialised tool to help decision makers follows a multi-criteria assessment based on four types of spatial constraints (attractiveness, repellence, regulatory and incentive); but also the fact that attributing these constraints to all the geographical objects contained in the GIS data selected must be possible. Here we consider that attractiveness belongs to BAU and repellence belongs to NIMBY perception’s values of any stakeholder.

The procedure chosen is combinatory because the integration of the ensemble of the spatial constraints for each of the GIS data selected is needed in order to produce a spatialised result in GIS.

A vector data’s combination induces the problem of the numerous artifacts that are created while crossing multiple data. It is a consequence of the discreet geometry of the vector objects, which do not coincide between layers.

The combination of raster data (Fig. 2), on the contrary, allows the use of a common grid. It offers a rigorous superimposition of the layers and the possibility to realize algebraic treatments of grids on quantitative (all types of calculus), as well as qualitative (mostly for logical computations) data.
Raster data can be obtained by rasterization of vector data. It enables the integration of vector data in raster databases.

The use of raster data predominately permits the mobilization of numerous tools for spatial analysis, especially for the modeling of continuous phenomena in space (for instance the distance considered, in the project, as attractive or repellent).

It was decided to use the Euclidian distance’s calculus tool (from ArcGIS spatial analyst tool box, Fig. 3) in order to assess attractiveness and repellence constraints. It is motivated by the fact that this tool allows to model a gradient in a 2D plan, and therefore to measure an increasing, or decreasing phenomenon in space.

This device uses a concept that is sufficiently explicit for the assessment model of spatial constraints to be understandable by a wide class of users, decision makers and local communities. It is based on the notion of positive or negative externality, and is close to the hedonic prices’ method used in environmental economy [17]: the value of the constraint is a decision cost that allows to accept or decline a spatialised scenario issued from the combination of the four types of constraints available, possibly weighted by the decision maker.

Users can implement this tool rapidly and effortlessly. A large number of location scenarios can thus be quickly produced, and these scenarios can be further refined in an interactive manner by a decision maker.

B. Trading information at regional scale

1) Producing constraints’ layer

An attractiveness constraint (Fig. 4) corresponds to an investigation of the proximity in relation to an attractive element in an urban, or regional context. The shorter Euclidian distance to reach the objective is therefore the one offering the lowest constraint.

A repellence constraint (Fig. 5) corresponds to an investigation of the remoteness in relation to a repellent element in an urban, or regional context. The shorter Euclidian distance to reach the objective is therefore the one offering the highest constraint. A repellence constraint is decreasing in space whereas an attractive constraint is increasing in space.
In the GIS used, there is no spatial analysis tool to process an inverse distance calculation. In order to obtain this result, a grid algebra tool must be used as follows:

\[
\text{InvRastDist} = (\text{RastDist} - \text{DistMax}) \times (-1)
\]

where RastDist = distance raster; InvRastDist = inverse distance raster; DistMax = maximum value of RastDist.

To be able to combine the ensemble of the distances, and inverse distance rasters (in other words to combine attractiveness and repellence constraints), a normalization of the distance values is necessary in order for 1) the maximum value to be equal to 1 (the maximum constraint) and 2) the minimum value to be equal to 0 (the minimum constraint).

This data normalization is realized by the maximum value in order to obtain a gradient of constraints spanning from 0 (constraint null) to 1 (maximum constraint) for each raster calculated. For inverse distance raster, the result of the normalization is multiplied by -1 in order to keep positive values varying between 0 and 1.

The normalized distance rasters are expressed as follows:

\[
\text{RastDistNorm} = \frac{\text{RastDist}}{\text{DistMax}}
\]

and

\[
\text{InvRastDistNorm} = \frac{(\text{RastDist} - \text{DistMax})}{\text{DistMax}} \times (-1)
\]

where RastDist is distance raster; RastDistNorm is normalized distance raster; InvRastDistNorm is the normalized inverse distance raster; DistMax is the maximum value of RastDist.

In the cases of both constraints (attractiveness and repellence), the processed data varies between 0 and 1, following rigorously opposed directions. It allows the combination of constraints rasters obtained in coherence with the concepts used. The assessment of the two other constraints (regulatory and incentive) is even easier.

The regulatory constraint is considered as a surface area to be excluded from the final scenario. It is equivalent to a partition of the spatial analysis plan between regulated areas and areas considered as free (from a regulatory point of view). Example can be, at regional scale, the impossibility to build an industrial site in the protected perimeter of a drinking water well.

The incentive constraint is considered as a surface area relevant to an opportunity (development fund, politics, soil use...) to plan the implantation of industrial or storage facilities.

The assessment of these two constraints corresponds to the elaboration of a binary raster (0 or 1). Here again, values are inversed between regulatory and incentive constraints.

For regulatory constraints, all surface areas subject to legal prohibition or recognized as impossible to plan by a territorial agent or a decision maker, have 0 as value. The other surface areas are equal to 1 (Fig. 7).

For incentive constraints (Fig. 8), all surface areas offering the opportunity of development or recognized as so, have 0 as value when the other surface areas are attributed the value of 1.

![Fig. 6. Regulatory constraint – Drinking water wells’ protection perimeter.](image)

![Fig. 7. Incentive constraint – Coastal development fund area.](image)
2) Combining the different constraints by grid’s algebra

Four types of spatial constraints formatted as a raster are therefore available for the combinatory analysis by grid algebra. Attractiveness, repellence and incentive constraints’ rasters are integrated by summing, when the regulatory constraints’ raster is integrated by multiplying. For a scenario where four constraints are taken into account (thus 4 rasters), the calculus is as follows:

\[ \text{RastScenCont} = \frac{(\text{RastAtt}+\text{RastRep}+\text{RastInc})}{3} \times (\text{RastReg}) \]

Where RastScenCont is the raster of the scenario of constraints, in other words the result raster of the integration calculus of the four constraints; RastAtt is the attractiveness constraint’s raster; RastRep is the repellence constraint’s raster; RastInc is the incentive constraint’s raster; RastReg is the regulatory constraint’s raster.

3) Creating scenarios by weighting spatial constraints

The direct integration of all the spatial constraints’ rasters available can be considered as a reference scenario. However it does not take into account the diversity of the decision makers’ points of view or the relative value of a constraint compared to another. In other words, is it more important to be close to main roads or more important to be close to potential deconstruction sites? An informed decision maker would judge that it is meaningful to modulate this relative importance. As a matter of fact, there is no good decision without weighting the decisional criteria, especially when they are numerous. It is also convenient to prioritize and determine the most relevant criteria and their relative importance.

Moreover, the pertinence of a criterion (selection, or non-selection of a spatial constraint), or its relative importance (weights in relation to the ensemble of the criteria retained) depends on the point of view and the expertise of every stakeholder involved in the decision process. Eventually, as shown in figure 9, the injection of certain constraints can have a very significant impact on the decision’s scenario (for instance to consider an incentive constraint as equivalent in terms of weight to the other constraints). The system must therefore be open, modular from a catalog of constraints constituting the primary decisional material.

III. TOWARD FUTURE APPLICATION: NORD-PAS-DE-CALAIS REGION

A. Data set and scenario building

Table 1 accounts for the data used for Ceamas research project in the Nord-Pas-de-Calais-Region. It consists of 44 potential constraints (or parameters) classified in 7 themes, which are land use, coastal areas, natural areas, hydrological, industrial, transports and economical constraints. Different data sources were used to gather this information:

- CARMEN, 2015 (http://carmen.naturefrance.fr),
- EEA (European Environmental Agency),
- BRGM, 2008 (French Geological Survey),
- AEAP, 2008 (Artois-Picardie Water Agency),
- BD Carthage, 2009 (from the Forest and Geographical Information National Institute (IGN), http://professionnels.ign.fr/bdcarthage),
- BD carto IGN, 2010 (http://professionnels.ign.fr/bdcarto),
TABLE I. GIS DATA SET USED IN THIS RESEARCH - With: PNR: REGIONAL NATURAL PARKS; ZNIEFF: NATURAL ZONES OF ECOLOGICAL, FAUNAL AND FLORAL INTERESTS (1 FOR HOMOGENEOUS SMALL AREAS; 2 FOR HETEROGENEOUS LARGE AREAS); EEZ: EXCLUSIVE ECONOMIC ZONES; ZRR: RURAL REVITALIZING ZONES; FADL: COASTAL DEVELOPMENT’S HELP FUND; ZPAT: PRIORITY ZONES OF TERRITORIAL PLANNING; ZRDP: RURAL ZONES OF PRIORITIZED DEVELOPMENT.

<table>
<thead>
<tr>
<th>Themes</th>
<th>Constraints (or parameters)</th>
<th>Data sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land use</td>
<td>Urban fabric</td>
<td>CORINE LC</td>
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<td></td>
<td>Airports</td>
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<tr>
<td></td>
<td>Dump sites</td>
<td>&quot;</td>
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<td></td>
<td>Artificial non-agricultural / vegetated areas</td>
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<td></td>
<td>Arable land</td>
<td>&quot;</td>
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<td></td>
<td>Permanent crops</td>
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<td></td>
<td>Pasture</td>
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<td></td>
<td>Heterogeneous agricultural areas</td>
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<td></td>
<td>Forest</td>
<td>&quot;</td>
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<tr>
<td></td>
<td>Shrub and herbaceous vegetation</td>
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<tr>
<td></td>
<td>Inland wetlands</td>
<td>&quot;</td>
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<tr>
<td></td>
<td>Inland waterbodies</td>
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<tr>
<td>Coastal areas</td>
<td>Dunes, beaches, sands</td>
<td>CORINE LC</td>
</tr>
<tr>
<td></td>
<td>Salt marshes</td>
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<td></td>
<td>Intertidal flatlands</td>
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<td></td>
<td>Dumping sea sites</td>
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<tr>
<td></td>
<td>Coastal erosion</td>
<td>&quot;</td>
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<tr>
<td>Natural areas</td>
<td>Biotopes’ protection</td>
<td>CARMEN</td>
</tr>
<tr>
<td></td>
<td>Nature’s hearts</td>
<td>&quot;</td>
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<td></td>
<td>Areas to re-naturalize</td>
<td>&quot;</td>
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<td></td>
<td>Natura 2000</td>
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<td></td>
<td>PNR</td>
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<td></td>
<td>Ramsar</td>
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<td></td>
<td>Natural reserves</td>
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<td>Natural inventory (inscribed sites)</td>
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<td>Natural inventory (classified sites)</td>
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<td>Bird conservation important zones</td>
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<tr>
<td></td>
<td>ZNIEFF 1</td>
<td>&quot;</td>
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<td>ZNIEFF 2</td>
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<tr>
<td>Hydrological</td>
<td>Drinking wells</td>
<td>BRGM</td>
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<td></td>
<td>Protected areas</td>
<td>AEAP</td>
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<td></td>
<td>Protected ground water areas</td>
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<td></td>
<td>Streams</td>
<td>BD Carthage</td>
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<td>Industrial</td>
<td>Ports</td>
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<td></td>
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<td></td>
<td>Active quarries</td>
<td>BRGM</td>
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<td></td>
<td>Geological aggregate use</td>
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<tr>
<td>Transports</td>
<td>Waterways</td>
<td>BD carto IGN</td>
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<td>Roads</td>
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<td>Economical</td>
<td>EEZ</td>
<td>Eurostat</td>
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<td></td>
<td>ZRR</td>
<td>SIGALE</td>
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<td>FADL</td>
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<td>ZPAT</td>
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<td></td>
<td>ZRDP</td>
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</table>

Building a decision scenario from this GIS dataset consists in selecting appropriate spatial constraints (i.e. parameters) from a stakeholder point of view, applying weight to each selected constraints according to stakeholder’s values, computing a scenario by mean of map algebra (i.e. Raster Calculator tool in ArcGIS spatial Analyst® tool box), and displaying the resulting map for validation from the stakeholder.

**B. Results and discussion**

Two decisional scenarios (Fig. 9 and Fig. 10) have been computed with a selection of various parameters. Scenario 1 (Fig. 9) is a decision case where 6 parameters are selected from the 44 available.

In this case, the main objective is to locate areas of low constraints where ports sediments can be re-used. Roads, ports and urban locations are attractive whereas quarries are repellent. The coastal development fund (incentive economic parameter) and the drinking wells protection perimeters (regulatory not permitted area) are also included in the decision. Weighted parameters values aim at reducing the transportation costs and increasing the economical competitiveness against quarries.

Scenario 2 (Fig. 10) is a decision case where 8 parameters are selected from the 44 available. In this case, the main objective is to locate areas of low constraints where quarries are associated with the marine sediment resource and where waterways are added to roads for sediment transportation (i.e. all parameters are positive). Quarries locations are included as positive constraint to compute a decision scenario where all aggregate resources are shared to deliver the area of interest. Drinking wells protection perimeters, Ramsar and Natura 2000 sites (i.e. regulatory, not permitted area) are also included in the decision. Weighted parameters values aim at are calculated in the objective of reducing the transportation costs and of increasing the environmental constraint for potential re-use in the area of interest.
Scenarios 1 and 2 give very different decision maps depending on the number of constraints selected and the applied weights given by "simulated" stakeholders. This spatial DSS is therefore very sensitive and user driven. The final decision has to be built according to a stakeholder process in which each stakeholder has to define his own maximum constraint’s threshold value for scenario validation. Then by spatial combination it is possible to map each validated decision area but also the potential spatial consensus between stakeholder 1 and 2 decisions according to their own sets of values (Fig. 11).

Spatial consensus (Fig. 11) is a strategic area where stakeholders scenarios overlap according to their own decision’s rule set. This common area of interest can then be used for different purposes, including a logistical analysis [18], [19], [20], [21] between potential civil engineering applications or a GIS accessibility analysis [10], [2], [3], [4]. In both cases, the spatial consensus area among stakeholders helps a lot in reducing the amount of potential location to be analyzed. Moreover reducing the threshold value for scenario validation, and/or introducing more stakeholders in the decision process will modify the spatial consensus area of interest accordingly. This spatial DSS is indeed a tool to support the decision process among stakeholders by helping them by:

- sharing a territorial vision between involved stakeholders,
- ensuring that their own decision rules are feeding the DSS and play a role in the final decision,
- mapping the spatial consensus as an area of interest for strategic level’s decision making,
- reducing the need of socio-economical information to select and perform an operational application,
- reducing the number of calculations when using accessibility analysis or logistic models at high geographical scale for operational implementation.

IV. CONCLUSION

The spatial DSS implemented in CEAMaS project aims at being Participative GIS (PGIS) applied to marine sediment re-use in civil engineering application. In this procedure the stakeholder is driving the scenario building and keeps control on every step to reinforce his final trust in the decisional scenario. Moreover each stakeholder can play around with ease in selecting both constraints and weights making this methodology a very flexible tool for project planning at strategic level of decision.

The final aim of this Spatial DSS tool development is to provide the end user with a transparent system from which stakeholders can learn about their own vision of spatial opportunity for marine sediment re-use. This methodology has shown its potential to locate the spatial consensus from which decisional consensus can be discussed among involved stakeholders.

This tool will be tested within CEAMaS project with different stakeholders in Nord-Pas-Calais region France but also in Southern and eastern Ireland at EU Nuts 2 level. A sensitivity analysis will also be undertaken for constraints selection, parameter weighting, scenario’s validation and threshold values used to open or close the area of interest in the spatial consensus building process.

This methodology could be potentially used for any spatial location problem involving multi-stakeholders participation and environmental constraints. It can also be used to map individual perception of environmental impacts.
References


