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# An Integrated GIS Methodology to Assess the Impact of Engineering Maintenance Activities: A Case Study of Dredging Projects

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**Abstract:** Engineering infrastructures require regular maintenance and/or repair activities that have important social, environmental, and economic impacts. Despite their growing importance, few studies have focused on fully integrated analyses. This work presents a general methodological approach to design databases of engineering maintenance activities for their assessment. This methodology was applied to the case of dredging projects in the ports managed by the Andalusian Regional Government (Spain). The resulting database contains 87 fields of information obtained from the analysis of 70 activities performed between 1993 and 2015. This database is free, public ,and available to the scientific community, and it was implemented in PostgreSQL using the PostGIS extension for spatial data; therefore, it can be integrated in a GIS. The assessment of deviations from the initial projects and the comparison between locations enhanced our methodology, which represents a valuable tool not only for scientists and managers to improve the decision-making process when planning future strategies, but also to evaluate the environmental impacts.

**Keywords:** GIS integration; engineering maintenance activities; methodology; dredging; database; cost-efficient; environmental impact; PostgreSQL

## 1. Introduction

The complexity of environmental management has increased in recent decades, with higher demands for considering multiple economic, environmental, and ecological factors [1]. The environmental management industry has gradually become sophisticated in the use of technology as more stakeholders are involved, better tools are developed, and requirements for openness and accountability increase [2]. Many environmental issues can benefit from a multidisciplinary assessment provided by integrated modeling. In this way, many researchers highlight the need to solve complex real-world problems involving the environment and its relationship to human systems and social and economic activities [3,4].

Engineering infrastructures are fundamental for the worldwide development of societies and have increased significantly over the last century. Although emphasis has traditionally been placed on the design and construction of infrastructure, it is now commonly recognized that structures must not only be built but also maintained and ultimately replaced because of failures, deterioration, aging, and obsolescence [5]. Moreover, the concept of sustainability extends to engineering infrastructures and has implications for improving the recycling of building materials [6] and minimizing water, air, and land pollution [1]. Because infrastructure is traditionally financed by public governments, economic sustainability has been an increasing demand from society in recent years [7,8]. However, the field of infrastructure engineering frequently does not benefit from the developments in environmental management because many worldwide administrations keep archives of documents in an inefficient paper format.

Dredging activities at ports are a valuable example of regular maintenance activities for engineering infrastructure that have environmental and economic implications. Although they are necessary for the development of coastal countries [9], operations and activities in harbors also have several drawbacks [9–13], such as reduced water quality [14], gas emissions [15], air pollution [16], and sediment contamination [17–19]. In particular, the dredged sediment is generally polluted [20] and should be treated with caution. The complexity of these problems was highlighted in the European Sediment Research Network EU-funded project, in which "dredging" and "dredging disposal" were the second and third of the top ten environmental issues at ports [21]. Contemporary ports should operate in a more environmentally friendly manner due to the increasing awareness and concerns of their stakeholders [22] and regulations and directives [23,24]. This demand is greater for leisure harbors (marinas), in which the Blue Flag award implies the achievement of significant environmental standards. Overall, there is a real need to use and combine all available methods and tools when exploring the effects of dredging interventions in natural systems [25].

This article presents a methodological approach to assess the impacts of regular maintenance activities of engineering infrastructures that is applied to a case study of Andalusian (southern Spain) ports. This region, which includes 53 ports, requires regular maintenance dredging activities that cause unsustainable investments and environmental impacts that are difficult to control and assess. Managers are demanding integrated strategies to minimize these impacts and improve the reutilization of the material whenever possible. These approaches are similar to those being applied in other disciplines, such as fishing [26], forests [27], glacier dynamics [28], and soil mapping [29]. Our methodology accounts for the complexity of the documentation involved in engineering projects, which is frequently modified during the construction phase.

## 2. Case Study

The region of Andalusia (southern Spain) has 1100 km of coastline. Andalusia is surrounded by the Mediterranean Sea and the Atlantic Ocean, which are connected by the Strait of Gibraltar (Figure 1). Fifty-three ports are located along this coastline (Table 1), which is an average of 1 port every 21 km.

Thirteen ports are owned and operated by the Spanish National Government, and the others are managed directly or indirectly by the Andalusian Regional Government, which is responsible for the maintenance and repair of the facilities as well as for the development and management of the infrastructure. This study focuses on the analysis of the 20 ports that are directly managed by the regional government in which at least one dredging operation has been undertaken (Figure 1).

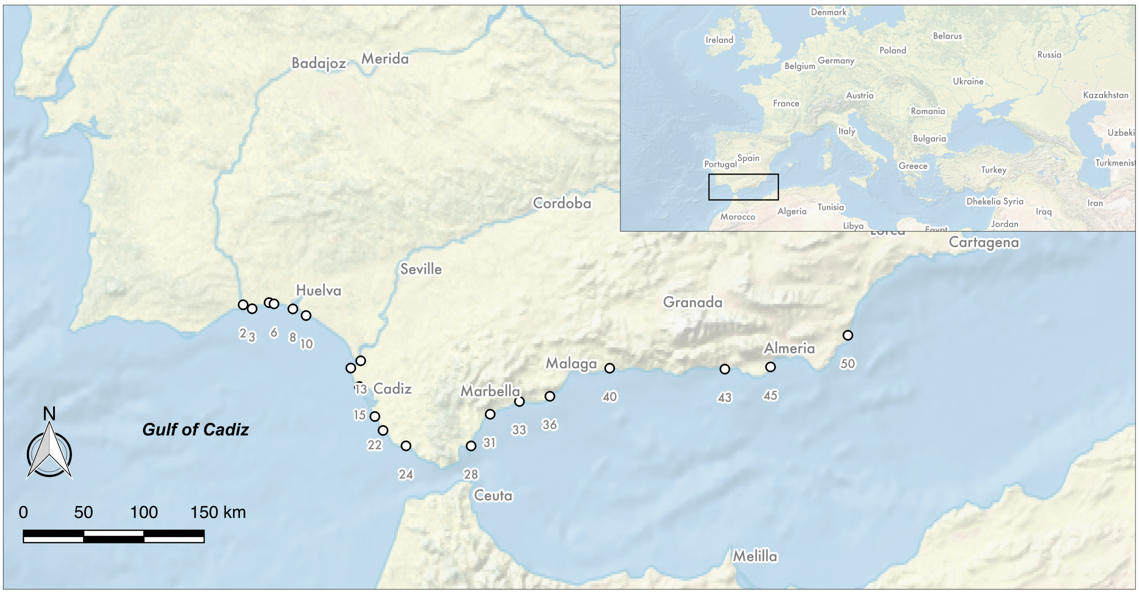


**Figure 1.** Study area and locations of the ports in the Andalusia region of Spain (Table 1). The numbers increase from West to East and correspond to the information in the database. The analyzed ports are directly managed by the regional government, and comprise of those in which at least one dredging operation has been done.

**Table 1.** Andalusian ports classified by province and activities (leisure, fishing, and commercial). Asterisks (*) indicate refugee purposes. Ports can be directly (underlined) or indirectly (italics) managed by the Andalusian Regional Government. Andalusian ports managed by the National Government are in bold.

| PROVINCE | LEISURE | FISHING | COMMERCIAL |
|---|---|---|---|
| HUELVA | 1,2,3,5,6,8,10 | 2,3,5,6*,8 | |
| | *4,7* | | |
| | **9** | **9** | **9** |
| SEVILLA | 12 | | |
| | **11** | | **11** |
| CÁDIZ | 14,15,19,21,22,23,24 | 13,14,15,22*,23,24,28 | 24 |
| | *29* | | |
| | **16,18,20,26,27** | **18,20,25,26** | **17,18,20,25,26** |
| MÁLAGA | 31,36,40 | 31,36,40 | |
| | *30,32,33,34,35,37,39* | *34* | |
| | **38** | **38** | **38** |
| GRANADA | | | |
| | *41* | | |
| | **42** | **42** | **42** |
| ALMERÍA | 43,45,50,51,52,53 | 43,45,50,51,52,53 | 51 |
| | *44,46,48* | | |
| | **47** | **47** | **47,49** |

## 3. Methodology

In this study, we propose a useful methodology that is based on the compilation, organization, and analysis of several fields of information about the maintenance activities associated with a given engineering infrastructure (i.e., roads, railways, ports, or bridges). We applied this methodology to the case study, which resulted in a dataset that was integrated in an open and public database and incorporated into GIS systems for further analysis.

### 3.1. Scheme of the Methodology

To unify, clarify, and collect the information in an interchangeable way, we developed a strict methodology that ensures the consistency of the results. The phases of the methodology are (Figure 2):

1. Phase 1: Collection of activities. The information is collected and classified by location.
2. Phase 2: Organization of the documentation. The information about each location is organized into two groups: consulting (associated with the initial design of the project) and construction (associated with the final construction project and the executed works) information.
3. Phase 3: Analysis of two selected activities to design the guideline table. Two representative activities are chosen with the managers as examples and benchmarks to select the fields of data to be included in the database. The most relevant variables are then grouped and organized into the first table design. The variables are reviewed, and the table is redesigned if necessary. A final table and set of variables are developed.
4. Phase 4: Completion of the final table. This step consists of collecting the data for all of the activities. Although many variables are similar to other types of engineering maintenance activities (see Table 2), other specific data may be collected for further analysis depending on the type of activity. In our case, Table 2 includes data about the maritime climate. The variables highlighted in color appear in both the consulting and the construction information and provide the basis for further comparisons and the development of management strategies. As in Phase 3, periodic revisions by the working team are recommended to avoid inconsistencies.
5. Phases 5 and 6: Incorporation into a database and GIS integration. The final steps consist of the incorporation of the information into a database and the full integration into a GIS. These phases are further described in the next section.

The time required to revise and compile all of the information (Phases 1–4) depends mainly on the number of activities and variables, including the format of the information. The development of the database in this article took 5 months.

### 3.2. Development of the Database and GIS Integration

The object-relational database PostgreSQL was selected to store the information. This database management system has several notable features. PostgreSQL can handle spatial attributes such as points, polygons, or lines using the PostGIS extension [30], which makes it possible to perform spatial queries of the database [31]. In addition, it can be easily linked to the statistical language R, which provides libraries for statistical analysis. Another advantage of PostGIS is that it can be linked to the open source GIS Quantum GIS (QGIS), which provides tools for raster, vector, and point analyses as well as image processing.

In this work, the data were incorporated into a PostgreSQL/PostGIS system (https://gdfa.ugr.es/dragaport_data). QGIS conveniently integrates these representational models and was used to depict the data and develop the different types of maps in this work. Digital geodatabases allow the accumulation of large amounts of information that can be readily accessed with simple tools and are used in many fields of applied geography [28,32–34]

Some of these tools were successfully applied in [35], who presented an open database of 294 sites that showed shoreline undulations. This was a significant achievement regarding the development of databases for decision-making processes, providing part of the framework for the present work. This framework, which can be extended to any other activity, should be accessible using freely available and open source software when possible.

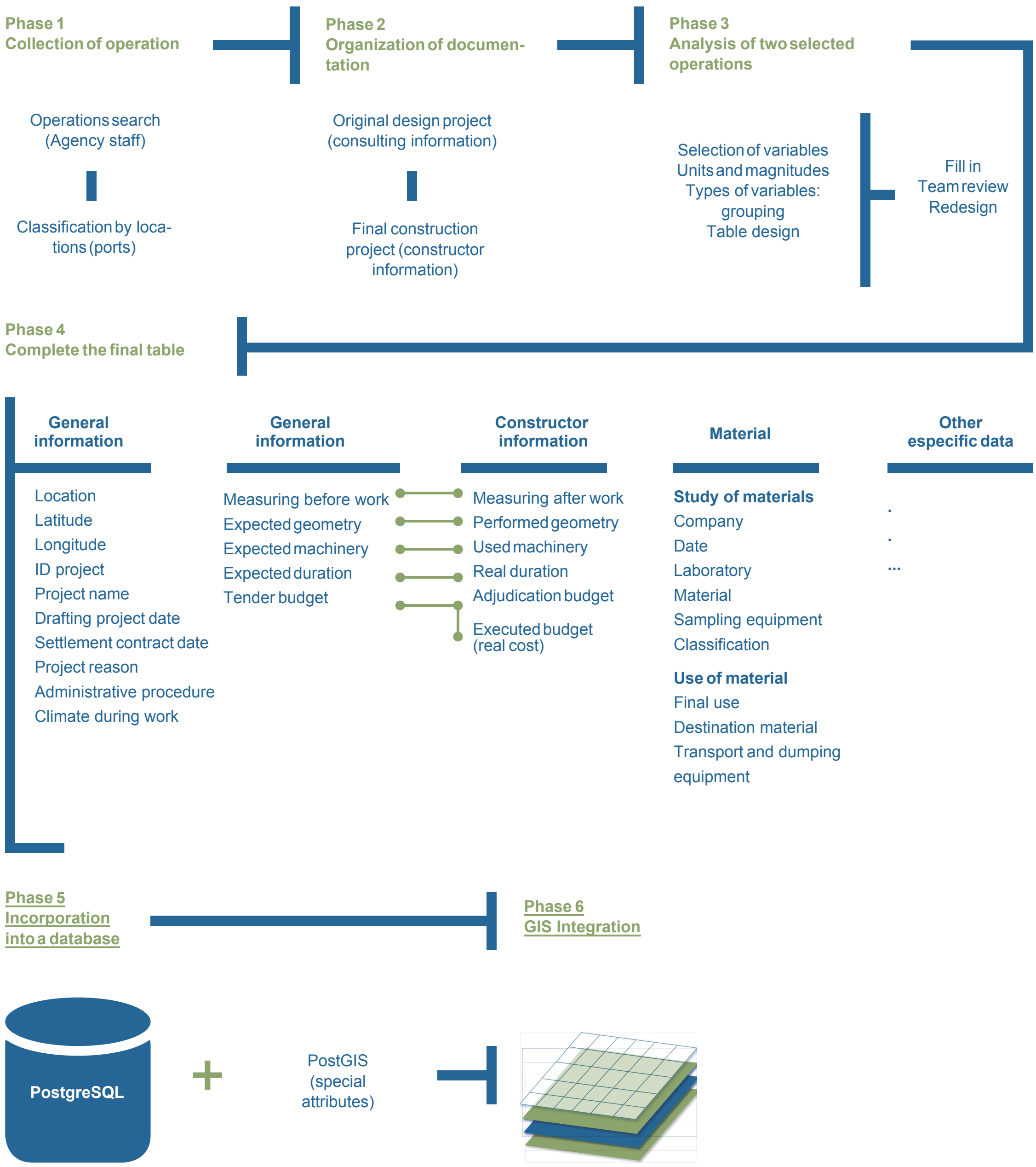


**Figure 2.** General scheme of the developed methodology to create databases from regular engineering maintenance activities.

## 4. Application to the Case Study

From 1993 to 2015, the regional government performed 70 dredging projects. A total of 87 fields of data were defined (Table 2); many of them are similar to other engineering maintenance activities, although some others may be different (i.e., the geometric parameters). The information in the global database and the stored geographical information are offered in both a browsable modern web platform and as a PostGIS layer. Because the information is well-structured and organized in the database, it is possible to query the data and sub-group the information using a query language, such as SQL. Thus, the processed information can be summarized and used to identify trends or patterns within the data using data mining techniques.

**Table 2.** Detailed information included in the dredging database obtained following the methodology summarized in Figure 2.

| | | TERM | UNITS | RANGE |
|---|---|---|---|---|
| **General information** | | | | |
| | | Location (city, village) | Nominal | - |
| | | Latitude | Coordinates | 36.19–37.23° |
| | | Longitude | Coordinates | −1.90–7.41° |
| | | Harbor name | Nominal | - |
| | | Project ID | - | - |
| | | Project name | Nominal | - |
| | | Drafting project date | - | 1993–2014 |
| | | Start date | - | 1993–2011 |
| | | End date | - | 1993–2011 |
| | | Contract settlement date | - | 1994–2012 |
| | | Project purpose | Nominal | - |
| | | Administrative procedure | Nominal | - |
| | | Machinery used | Nominal | - |
| | | Duration of the work (real duration) | Months | 01-dic |
| | Geometry | | | |
| | | Dredging area | $m^2$ | 1900–6,937,672 |
| | | Reference level | - | - |
| | | Slope gradient (H-V) | - | 0:1–10:1 |
| **Consulting information** | | | | |
| | | Consulting firm | Nominal | - |
| | | Machinery (suggested) | Nominal | - |
| | | Expected duration | Months | 0.25–12 |
| | Previous bathymetry | | | |
| | | Company | Nominal | - |
| | | Date | - | 1992–2015 |
| | | Time zone | - | 29–30 |
| | | Projection system | - | - |

**Table 2.** *Cont.*

| | | TERM | UNITS | RANGE |
|---|---|---|---|---|
| **Consulting information** | | | | |
| | Geometry | | | |
| | | Expected maximum dredging depth | Lowest astronomical tide (LAT) | −2.5/−10 |
| | | Expected dredging volume | $m^3$ | 3000–924,359.05 |
| | | Expected additional dredging volume | $m^3$ | 1318.68–45,000 |
| | Budget | | | |
| | | Execution budget | € | 7,954.46–6,053,158.45 |
| | | Overhead cost | % | 13 |
| | | Industrial profit | % | 6 |
| | | Tender budget (before VAT) | € | 9465.80–23,093,074.08 |
| | | VAT | % | 15–21 |
| | | Tender budget | € | 10,980.33–8,355,779.93 |
| **Construction information** | | | | |
| | | Construction company | Nominal | - |
| | | Machinery used | Nominal | - |
| | | Expected duration | Months | 0.25–19 |
| | Bathymetry after works | | | |
| | | Company/enterprise | Nominal | - |
| | | Date | - | 1993–2015 |
| | | Time zone | - | 29–30 |
| | | Projection system | - | - |
| | Geometry | | | |
| | | Maximum dredging depth | LAT | −2.5/−10 |
| | Modifications | | | |
| | | Geometry and dredging level modifications | Nominal | - |
| | | Real dredging volume | $m^3$ | 5040–299,328.03 |

**Table 2.** *Cont.*

| | | TERM | UNITS | RANGE |
|---|---|---|---|---|
| **Construction information** | | | | |
| | Budget | | | |
| | | Execution budget after modifications | € | 139,916.61–2,272,680 |
| | | Allocation coefficient | - | 0.58–1 |
| | | Reduction of tender | % | 0–100 |
| | | Adjudication budget (before VAT) | € | 9,015.18–5,491,86.50 |
| | | VAT | % | 15–21 |
| | | Adjudication budget | € | 10,457.61–6,370,568.62 |
| | | Budget increase | € | 0–41,784.25 |
| | | Adjudication budget (total) | € | 10,457.61–6,370,568.62 |
| | Final cost | | | |
| | | Draft execution budget | € | 7,434.77–2,501,556.40 |
| | | Overhead cost | % | 13 |
| | | Industrial profit | % | 6 |
| | | Average executed budget (before VAT) | € | 8,426.19–2,051,014.25 |
| | | VAT | % | 15–21 |
| | | Average executed budget | € | 9,774.38–2,420,196.82 |
| **Materials** | | | | |
| | Sediment samples | | | |
| | | Company | Nominal | - |
| | | Date | - | 1993–2015 |
| | | Laboratory | Nominal | - |
| | | Material | Nominal | - |
| | | Sampling equipment | Nominal | - |
| | | Sampling depth | Nominal | - |
| | | Granulometry | Nominal | - |
| | | Classification | - | I-II-III[1] |
| | | Volume according to the classification | $m^3$ | - |

1 * Categories based on the Recommendations for the Management of Dredged Material in the Ports of Spain, CEDEX.

**Table 2.** *Cont.*

| | | TERM | UNITS | RANGE |
|---|---|---|---|---|
| **Materials** | | | | |
| | Uses of dredged material | | | |
| | | Final use | Nominal | - |
| | | Destination of the material | Nominal | - |
| | | Radius of the circle | nautical miles | 0.25–1.75 |
| | | Material (extra dredging volume) | $m^3$ | - |
| | | Transport and dumping equipment | Nominal | - |
| **Maritime climate** | | | | |
| | | Wave height (H12) | m | 1–4.90 |
| | | Peak period (Tp) | s | 3.75–8.85 |
| | | Tidal range | m | 0.31–3.90 |
| | | Wave energy flux (module) | $kW \cdot m^{-1}$ | 0.63–3.98 |

### 4.1. Destination of the Dredged Material

One of the major economic engines of the Andalusia region is the coastal tourism sector; therefore, the quality of the beaches is a priority for managers. Nevertheless, recent erosion processes have had negative impacts on the development of this sector due to the deterioration of the beaches. During the 1990s, the reuse of dredging material from ports was practically non-existent, as shown in Figure 3. In contrast, 90% of the activities that were carried out during the last five years reused dredged material to replenish nearby beaches.

Spanish regulation requires that the decision taken by the administration regarding the reuse of materials be based on the physical-chemical characterization of the material. This database includes this information (when available) and allows the identification of restricted ports where difficulties in the management of the dredged sediment occur. This is the case for port n° 50, which is located in a protected area and where disposal sites are far from the coast because dumping at sea and along the beach is strongly restricted. In some other cases, the materials are subjected to special treatments. For example, in port n° 45, material must be dried before dumping. To deal with these environmental issues, new research on the reutilization of dredged material is being performed [36,37].


**Figure 3.** Evolution in the use of material removed by dredging activities performed by the Andalusian Regional Government in the last 20 years.

### 4.2. Cost Efficiency Assessment

The total investment by the Andalusian Regional Government over the last 20 years was 39,420,534.10 €, and the largest expenditure of 8,136,443.09 € (20% of the total) occurred in 2011. Based on the information in the database, many useful indexes and rates can be defined for further in-depth assessments. The administration frequently works with the average executed budget per activity at every port, which is calculated as the ratio between the total of the executed budgets and the number of activities. Port n° 6 has the highest cost (2,238,577.42 €), followed by port n° 45 (1,525,133.01 €). In both cases, costs increased due to particular environmental issues; the former is located in a protected area, which slows the work, and the latter has a particular problem with the final destination of the dredged material. In contrast, port n° 36 has the lowest cost (168,494.60 €).

The average cost of dredging 1 $m^3$ at each port was calculated as the ratio between the executed budget and the dredging volume. The highest cost was at port n° 45 (78.45 €) because special material treatments are required before the material reaches its final destination. The second highest cost was at port n° 5 (18.21 €), whereas the minimum cost was at port n° 23 (3.51 €). From a global perspective, dredging projects are more efficient in the Atlantic watershed; while the dredging volumes and costs by activity are higher, the mean cost of dredging 1 $m^3$ is lower (Atlantic: 6.28 €/$m^3$ vs. Mediterranean: 8.28 €/$m^3$). Hence, the assessment of the information in the database can inform the administration about regions that should be the focus of attention (i.e., improving the management of Atlantic ports due to the overall investment), but can also identify sites with specific problems (i.e., a deeper analysis of the dredging activities at port n° 45 is recommended).

### 4.3. Deviations from Original Projects

To properly manage engineering activities, one of the most useful parameters is the relationship between the expected data (before the projects) and the real data (after the projects) of a given variable in the database. We define the percentage of deviation as follows (Equation (1)):

$$P_D(\%) = \frac{D_R - D_E}{D_E} \cdot 100, \quad (1)$$

where $D_R$ and $D_E$ correspond to the real and expected data, respectively.

As an example, the results for the deviation of the budget are shown in Figure 4. The major underestimations (positive values) are found at ports n° 2 and n° 6 (up to 31%) in Huelva Province, whereas the greatest overestimation (up to 50%) is at port n° 23 in Cádiz Province. These results can help to predict the performance and behavior of future activities at a given site.

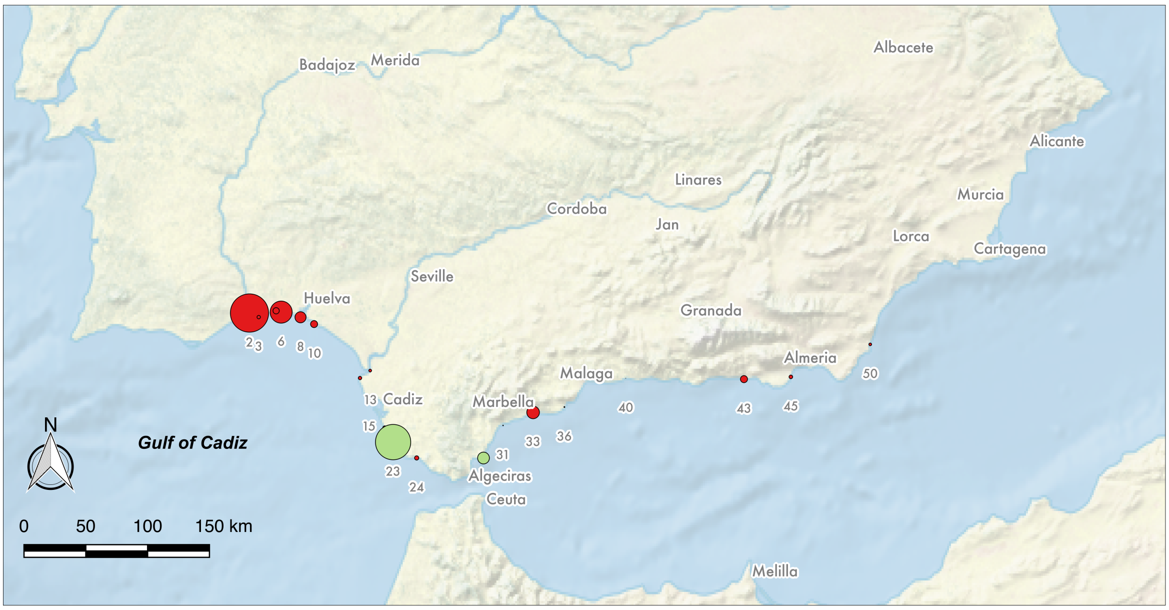


**Figure 4.** Percentage deviations of the budgets of the activities. Green (red) colors indicate negative (positive) deviations.

### 4.4. Applications of the Tool

In addition to the analyses shown in the previous sections, as well as the particular example of a port that will be shown in the following one, the methodology developed has a great potential and range of applications. One of them derives from improving the environmental impact studies associated with dredging, which depends to a great extent on the quality of the data related to the dredged material. Sediments absorb heavy metal, which are precipitated out of the water over time and become concentrated in the sediments below. When dredged, the sediment may act as a source of pollution, releasing high concentrations of heavy metals and altering the natural environment. A good dredging strategy would imply a higher lifetime of the interventions, which may reduce the environmental impacts and maintain the water quality and habitat conservation, and therefore, improve the sustainable management of altered systems.

The database developed also allows us to relate the dredging activities carried out with the most relevant maritime climate variables: significant wave height, incoming wave direction, peak period, or tidal range, among others. Thus, it is possible to precisely quantify the impact, for example, of the wave energy content on the performance of the dredging and to obtain average trends that allow the estimation of behavior patterns. Likewise, not only can the impacts of the activities be analyzed from an economic point of view in terms of volume and cost of dredging, but also in relation to the duration of the interventions (actual versus estimated duration).

It should also be noted that although the article shows the methodology applied to the case of dredging usually referred to as maintenance, it can be applied simply and directly not only to other usual activities in the field of coastal engineering, such as beach nourishment, but also to other areas of civil engineering, where maintenance activities are frequent and consume an important part of the budgets invested in infrastructure.

## 5. Punta Umbría (Huelva): An Example of the Database Potential

The port of Punta Umbría (port n° 8) is located inside the River Tinto-Odiel estuary, facing the Gulf of Cádiz (Figure 1). Since the late 50s, many new industrial and touristic activities have been developed in the surrounding area, with the consequent occupation of natural landscapes and the alteration of the natural behavior of the ecosystem. This occupation reduced the magnitude of the natural agents that maintain the stability of the navigation channel, causing a progressive growth of the sedimentation at the estuary mouth. As a consequence, periodic and urgent dredgings are necessary to maintain the navigation channel and guarantee safe conditions. Four interventions were done in the period of 2004–2014, with a total investment of 4,558,214.14 €. The volume of sediment dredged was the second highest (438,587.92 $m^3$) in Andalusia, representing 15% of the total volume dredged since 1993 by the Andalusian Regional Government. Figure 5 shows a detailed comparison of the impacts of the average dredging price, budget, and dredging volume of activities at the main ports depicted in Figure 1. Relating the port of Punta Umbría with the main Andalusian ports in terms of dredging interventions (three in n° 10, 2, and 50, four in n° 3 and 36, six in n° 31, eleven in n° 23), the average price of dredging 1 $m^3$ is one of the highest (Figure 5a), with an average cost per intervention of 1,140,000 €. In addition, the average price in Punta Umbría (10.39 €/$m^3$) was similar for the different interventions (between 8.88 and 11.03 €/$m^3$). However, for other sites, deviations are significantly higher (i.e., port n° 23). These variances are mainly due to the cost associated with the dumping or reuse of the material as well as the cost associated with the nature of the dredging activity (periodic vs. urgent).

Figure 5b shows the average executed budgets of the interventions. Punta Umbría is one of the ports where larger budgets were set aside for dredging interventions. In this case, there are very notable differences between the budgets, with deviations significantly higher than for the results depicted in Figure 5a. Overall, dredging volumes (Figure 5c) are similar in each intervention, with low deviations (i.e., ports n° 31, 36, and 50). In Punta Umbría, despite the lower volumes of dredging, cost investments are above average.

One of the main problems in Punta Umbría is the amount of sediment mobilized: at least one intervention is required every 2 (maintenance) or 4 years (urgent). Since most of the sediment is transported under storm conditions, we explored correlations between the storms (frequency, the number of storms, and associated energy flux) and the dredging operations (dates, volumes, and urgency/maintenance). Results are depicted in Figure 6. After a stormy winter (i.e., 2002–2003), a subsequent dredging intervention was done (summer 2004). The winters that followed (2004, 2005, and 2006) were of low energy and no interventions were necessary. However, during the winter of 2007 the number of storms slightly increased and finally, a dredging was done in summer 2008. A very energetic winter in 2009 followed this operation, resulting in a maintenance intervention in 2010. The winter of 2011 was mild, whereas in the winter of 2012–2013, a total of 9 storms arrived; hence, another intervention followed in 2014. One operation is required every four years at Punta Umbría;

this frequency reduces to two years if stormy winters arrive. For this site, one of the main forcings that must be considered when dredging is the wave climate and the resulting littoral drift, so alternative solutions may focus on reducing this rate.

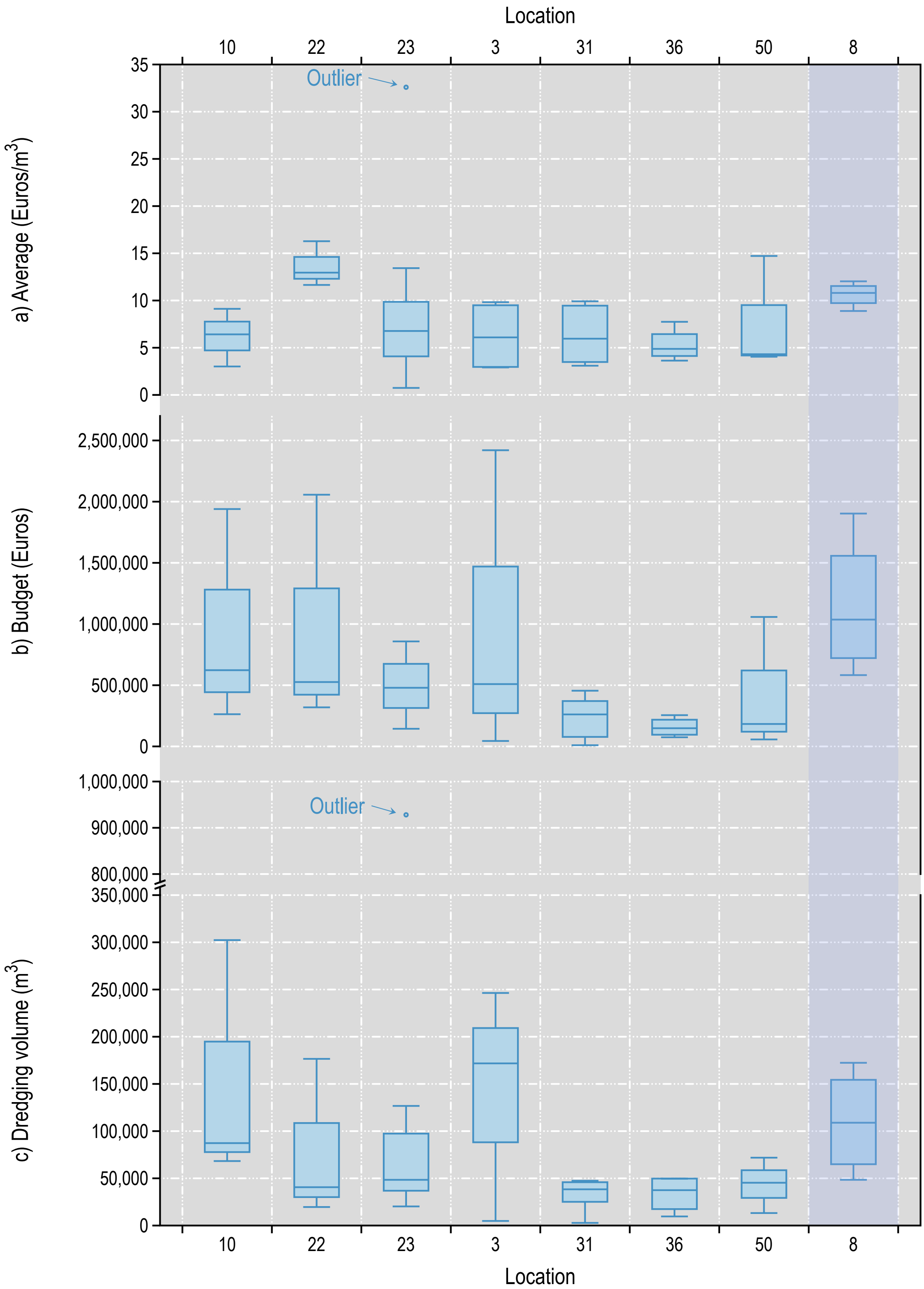


**Figure 5.** Box-plot showing the analysis of (**a**) the average price of dredging 1 $m^3$ of material, (**b**) executed budget of dredging activities, and (**c**) dredging volume of each activity. The main ports in each watershed are shown for a detailed comparison.

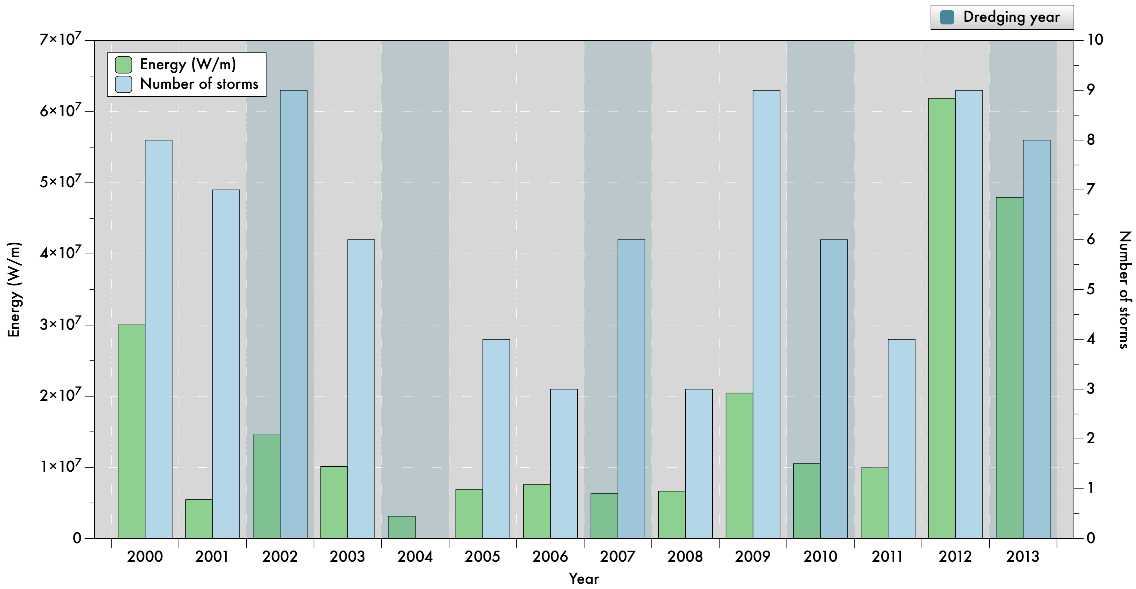


**Figure 6.** Relation between the number of storms, wave energy, and wave angle and the years of the dredging operations. The years in which dredging activities were carried out are shaded.

## 6. Conclusions

Engineering infrastructure requires regular maintenance activities, which have a significant impact on the environment and the economy. Despite their importance, few studies have focused on analyzing these types of activities in depth. In this study, we propose a general methodology to develop databases of civil engineering maintenance activities. Six sequential phases are established to gather and organize the information. The resulting database can be implemented in PostgreSQL using the PostGIS extension for spatial data and can therefore be integrated in a GIS, which is a valuable tool for the civil engineering discipline. It is also possible to query the data using a query language such as SQL, which allows subgroups of information that fit certain criteria to be obtained. The data can be gathered and expressed in a summary form for analysis. Thus, the processed information can be used to identify trends or patterns within the data.

The methodology was applied to the case of maintenance dredging activities in the ports that are managed by the Andalusian Regional Government (Spain). The database contains 87 fields of information that were collected after the analysis of the 70 activities performed since 1993 (https://gdfa.ugr.es/dragaport_data). The database was shown to be a valuable tool for identifying and analyzing the sites and the activities that have major impacts. Furthermore, assessments of the volumes, cost-efficiency, and deviations from the originally projected activities identify where future efforts for improving management strategies should focus to minimize environmental and economic impacts.

**Author Contributions:** P.M., M.Á.R.-M., and Á.T. designed the methodology and the database and wrote the draft of the manuscript. C.Z. and M.O.-S. analyzed the case study and summarized the main conclusions. All authors have read and agreed to the published version of the manuscript.

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