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ON THE APPLICATION OF THE POWER OF GIS TO ENVIRONMENTAL MEASUREMENTS FOR THE MONITORING, EXPLOITATION AND SUSTAINABLE ENVIRONMENTAL MANAGEMENT OF MARINE ECOSYSTEMS

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Abstract – Interest in sustainable environmental management of marine ecosystems is nowadays increasing rapidly as a result of the dramatic extending of man's economic activity in the vicinity of coasts, estuaries and deeper waters of the shelf edge and continental slope. Therefore, one needs to model the marine environment by setting up measurement procedures for evaluating natural and human impacts, which requires an interdisciplinary approach on multiple levels in order to predict its evolution with respect to environmental protection and the conservation of natural resources.

Remotely sensed oceanographic measurements in conjunction with geographic information system (GIS) may be a useful tool for defining strategies, for the monitoring of marine ecosystems over time and space and for the efficient updating of the marine environmental information. The GIS in marine ecosystems enables to integrate all relevant multilayer, spatial and temporal data acquired from the investigated marine environment, viz. high resolution bathymetry, characterisation of seabed, sediments and near sub-bottom, and the capability to query and display information for monitoring effectiveness.

This paper will outline through two examples of the potential use and application of GIS in monitoring, exploitation and sustainable environmental management of marine ecosystems. Some obtained results validate the suitability of GIS for this purpose.

Keywords: Marine Environmental GIS, Monitoring, Sustainable Environmental Management.

1. INTRODUCTION

During the last two decades, technological advances, urbanisation and industrial pressures, with activities such as ocean disposal for dredged mud, explosive disposal, wastewater disposal, commercial fishing, and research for new resources are today beside natural hazard known as the main causes of shifting of the natural equilibrium of an environment. The natural hazard impacts include both deterministic causes, such as long term variations in the climate yielding from systematic periodicities of an astronomical signature, e.g. melting of polar ice, as well as

stochastic causes, e.g. volcanic or tectonic activities, hurricanes, windstorms, coastal and river flooding, etc. These factors are dynamic, can change rapidly, and must be measured in real-time or near real-time to be useful for input into the environmental model for sustainable management.

Considering the marine ecosystems, there is a growing need to improve the understanding of the dynamic behaviour of these complex ecosystems under the pressure of technological trends, life style development and natural hazard. Furthermore, the nature of the marine environment and its vast size has necessitated the development of a wide variety of sophisticated equipment and techniques, systems and vehicles to improve management of marine resources and mitigate human and natural impacts. Until now, studies, which involve the ocean floor or the marine environment, have suffered from the disadvantage of an almost complete lack of accurate and adequate characterisation of the European seas. The main reason for these inaccuracies lies in the lack of a generally accepted versatile system for marine ecosystem characterisation. For example, many maps of the sea floor have been constructed with a wide range in navigational and depth accuracy, which are however considered inadequate to cover the needs of all marine technology applications.

Therefore, oceanographic instruments and techniques for remote investigation of the seafloor, rapid area assessment and better characterisation of the marine ecosystems in order to increase vertical and spatial resolution of the seafloor imaging and mapping for detailed sub-bottom morphology and seabed identification have changed drastically in the various disciplines involved in a marine study. This holds for sedimentology and stratigraphy in the discipline of marine geology, but also for biology, geochemistry, hydrography etc. The availability of data has also increased enormously.

The fact that the marine ecosystem is dynamic, the input data, which include complex interacting variables, have to be updated continuously in order to avoid environmental predictive modelling and management based on outdated information. The main goal is to model impacts of human activities and natural hazard on the environment and to supply resource management agencies, planners and

policy decisions with information that will enable them to manage and maintain the main components of the environment so that natural ecosystem functions can be recovered and equilibrium be maintained.

In this context, high-resolution seafloor mapping and surveys constitute a crucial element in most activities aimed at monitoring the marine environment and quantifying the impacts from human exploitation of the seafloor resources. The present monitoring and environmental surveying activities are still characterised by labour-intensive data acquisition, e.g. by visual diver surveys, bottom sampling, coring, etc. These measurements are obtained from instruments and equipment, which are proposed and operated by scientists belonging to many different disciplines. These data and information range from classical numerical values obtained from in-situ measurements and laboratory analysis of samples to descriptions and images including recent multi-media applications.

From this background, there is a general need for an appropriate and integrated system for integrating this variety of data and information obtained from developed instruments and equipment. In case the measurement input data are recorded on a rather continuous basis for a rather long period, e.g. a few years, or short time intervals expressed in days, hours or minutes and seconds, one hopes to be able to construct the GIS in such a way that it is able to monitor the observed site as well as to predict the future behaviour. The dynamic behaviour of the marine ecosystems may be difficult to detect in a tabular form but their spatial and temporal expression in GIS may provide the basis for further investigation.

2. IMPLEMENTING MARINE ENVIRONMENTAL GIS APPROACH

The process of sustainable environmental management is possible on the basis of the availability of geo-referenced data and the continuous monitoring of such up to date data sets, which involve enormous cost and scientific effort in instrument design, preparation and deployment and hence in data processing and analyses. Therefore, designing and building a spatial database for monitoring, environmental modelling and sustainable management of marine resources is considered as a main challenge for all people who are dealing with environmental GIS. GIS is not only a computer system, capable of input, data management (storage and manipulation), analysis, and output of geographic data, but in its widest definition a data system to manage the environment for sustainable development for the analysis of data, for planning, for decision making, and the implementation of decisions [1]. The use of GIS in this context could significantly increase the management potential of marine ecosystems.

Furthermore, the increasing capacity and speed of modern computers opens new doors towards the operational use of GIS. For continental or marine surveys, e.g. in the case of trials organised to model the environment, the use of GIS systems running on small but fast low cost computers, such as PCs or notebooks, becomes especially of interest

when the position of the observer site can be estimated accurately and displayed on a digitally prepared map automatically [2]. For marine purposes, all recorded data are to be located and referenced by geographical parameters, such as position (LL-co-ordinates), DTG (date-time group) etc., made available using Loran-C, Decca or [D]GPS (Differential Global Positioning System) receiver. All coordinates are normally expressed in WGS-84, which is the native format of the [D]GPS.

The implementation of the marine GIS is made more efficiently by GIS procedures, such as data pre-processing, database management, analysis and data representation, easy access by scientists, end-users and public through either database user interface or an open GIS graphical interface or Internet protocols. During this step of GIS implementation, particular attention is also paid to the accuracy of the spatial data. In fact, in defining accuracy as a measurement of exactness or correctness, care should be taken with respect to the resolution of error associated with digital spatial data as well with the accuracy of the instrument or equipment used during the monitoring step. To solve such problems, a real-time Differential GPS receiver is usually used in order to reduce data acquisition error during the sea trials.

The implemented marine GIS is based on a multilayer, topological database for the Electronic Charting and Display Information System (ECDIS) and on an object oriented database for the environmental data. This approach allows a fully integrated management of very different types of data, for instance, more and less fast variable spatial, geo-referenced data of high horizontal and vertical resolution in different layers, in two or three dimensions, objects, and tables of attributes (numerical and alphanumeric data).

Some pre-processing and conversion procedures are required before the storage of data in the marine GIS database. They consist of the following operations:

1. Spatial integrating of the data from different surveys by mosaicing and interpolation, with special care on navigational accuracy;
2. Vectorisation and reduction of data spatial redundancy due to oversampling. This is achieved along with converting the raster data into vector format and building the object oriented topological database. For this purpose, the TIN (Triangulated Irregular Network) model is applied, which allows nearly optimal representation of data which spatial variability differs significantly throughout the surveyed region.

The processed data allows statistical analysis, which contributes to modelling of the environment. Indeed, the next logical step in a marine GIS is to ask questions based on scientific criteria about the spatial relationships between different environmental parameters stored in the marine GIS database. These criteria make part of the environmental model, providing a framework for data selection and analysis. A variety of spatial queries can be performed to explore possible relationships between the different parameters identified as having a significant effect on ecosystem, and to model their effects in the area of interest by selecting one or many layers interactively. An understanding of such relationship is essential for interpreting environmental impact.

Hence, the designed and implemented marine GIS data include information about:

1. The high resolution bathymetry of the seabed;
2. The characterisation of the seabed, sediments and near sub-bottom;
3. The hydrological measurement results, e.g. vertical profiles of salinity and temperature;
4. Recognised geological forms in seafloor, e.g. slumps, faults etc.;
5. Other features and objects of investigated marine environment: flora, fauna, artificial objects etc.;
6. Other information: region description from other (e.g. historical) sources etc.

A complex data analysis GIS software package is therefore needed and used to interpret the information stored and to support:

1. Presentation and visualisation (in 2D and 3D) of bathymetry combined with the seabed, sediments and near sub-bottom characterisation, integrated with the presentation of other components of investigated marine environment, e.g. vertical profiles of oceanographic parameters. These functions possess a lot of features making them very convenient in use, e.g. multi-view, easy zooming, colours and additional processing selection (e.g. shading), 3D perspective viewing, etc.
2. Multilayer structures and easy creating of thematic maps, to present and classify various data properties in a user-defined manner.
3. Analytical spatial/attributes queries in a standard Structured Query Language (SQL).
4. Updating of database tables and spatial data, including combining, splitting, reshaping, and other processing of spatial objects.
5. Wide set of tools for analysis (e.g. statistical) of acquired data, with convenient forms of various results presentation.
6. Easy production of thematic maps containing the data and results of analysis procedures, with fully automated creating of description objects as legends, geographical co-ordinates grids etc.
7. Management of acoustic surveys (e.g. optimal survey design), to note only few.

3. DEVELOPMENT OF A MARINE G.I.S. WITH THE VIEW ON THE MONITORING AND THE MODELLING OF THE GUAYAS ESTUARY AND THE ESTERO SALADO IN ECUADOR, SOUTH AMERICA [3]

The first example describes the developed methodology and demonstrates how a large interdisciplinary marine GIS can be useful for criteria establishment. The project 'Development of a marine environmental GIS to monitor the Guayas estuary and the Estero Salado in the vicinity of Guayaquil in Ecuador' has been funded by ABOS (Belgian Agency for Cooperation and Development) and VLIR (Flemish Interuniversity Council, 1996-1999).

The aim of this research was to quantify and correlate in space and time certain actual aspects of the geo-bio-physical-chemical equilibrium in the Guayas estuary and the Estero Salado tidal channel, by means of a functional Geographical Information System (G.I.S.). The estuarine channels are located at a transitional marine environment in

the intersection of two important maritime fronts that can be described in terms of the autogenic input of climate, geomorphology, hydrology, tectonics, sedimentary, biological, estuarine, tidal, and ocean dynamics, and the anthropogenic front built up by the extended agricultural, domestic and industrial -including harbour- activities in the Ecuadorian Central-West and South.

The Guayas basin at Ecuadorian lowlands is a zone of elevated productivity among the context of South America. Morphologically, it is set-up by a rich hydrographical system that irrigates some 33.000 km² and at this location more than 30% of the Ecuadorian population resides, which is more than 2.500.000 inhabitants. An utmost important economical settlement takes place at this location, e.g. shrimp cultivation and banana plantations. This highly agricultural and industrial developed zone is directly facing the inner Guayas estuary, where a much relevant production of nutrients for the oceanographic system of the northwest Pacific takes place. An amount of 1746 industries of different kinds: food, paper, textiles, pharmaceuticals, etc., are present there as well.

The city of Guayaquil is most closely related to the Guayas estuary and the Estero Salado. Into these two aqueous environments all domestic, agricultural, industrial, and aqua cultural discharges are converged and from them, water and food resources such as fish, shellfish, crabs and other benthic macro-organisms, are exploited. Nevertheless, still a scarce knowledge exists of how these two systems are assimilating this input of organic and inorganic pollutants.

The shrimp farms, for instance, constitute a main focus of interest. The cutting of the mangroves for building shrimp ponds affects the ecosystem in a variety of ways, and the consequences can be sensed by different views. The natural protection against the erosive action of tides is diminished, together with the mangroves' capability of retaining nutrients and sediments for the building-up of the characteristic habitat of the site. A larger evaporation is favoured and the discharge from the shrimp ponds enriches the surrounding environment with a surplus of nutrients that may eventually contribute to eutrofication. This process constitutes a threat not only for the pond itself that gets its waters from the main channel, but also for the rest of the surrounding system.

Pesticides require also attention because of their extensive use in the zone and non-controlled input in the aqueous mass. Between 1983 and 1986, 107 different types for an amount of 27.715 tons were imported for agricultural and epidemic prevention use. The use of 19 of them, among others Pentachlore, Heptachlore, Chlordane, Dieldrin, Aldrin, DDT, has been officially prohibited since 1983 due to their long term capacity of being retained in soils and living organisms along the tropic chain and consequent hazardous implications for health. Nevertheless, the use of some of them has not stopped yet. Other pesticides, the use of which is accepted, hold copper, which is essential for life but becomes toxic at certain sufficiently high concentrations.

There are three concerns for identifying a polluted site once a potential contamination is observed: the aqueous

medium, the fine sediments, and the biota, especially the benthic organisms. The approach to understand the impact of pollutants brought in the system is to figure out their occurrence in function of time and space at the three media mentioned above. The project pretends to identify spatially and temporarily the preferential location of sites that are vulnerable for pollution.

A secondary output of this project contributes in a better understanding of the siltation dynamics at the channel of navigation to the Puerto Marítimo de Guayaquil. The goal was to identify the source and pattern of accumulation of fine sediments in order to provide supporting information to help to control the constant siltation along preferential sites along the channel that require frequent dredging to enable safe navigation.

Finally, attention was brought to the occurrence of a particular phenomenon that affects the Pacific coastline: the 'El Niño' event. A third output of this study was the identification in the sedimentary record of any pattern of occurrence or possible periodicities of this event that introduces, or has introduced a variety of modifications in the South-Eastern Pacific region.

The controlling factors for physical and chemical settings within the system of this study are various and complex:

- semi-diurnal tidal regime;
- characteristics of the spring-neap tidal cycles at the site;
- long term astronomic cycles;
- river discharge varying seasonally;
- extraordinary events as the phenomenon of "El-Niño" affecting the seasonal expected conditions;
- the geological frame with special attention to the last centuries to include climatic induced changes;
- the human induced impact during the last decades and for the future.

Therefore, in order to forecast slides from El-Niño and diseases in shrimp pound and to enable sustainable management in this region, a specific marine Guayas - Salado GIS was constructed. It consists of:

1. The marine spatial database of the transitional-marine area of Guayaquil, which includes a set of graphic elements such as points, lines, and areas, representing coastlines, depth contour lines (bathymetry), sand bar boundaries, buoys, beacons, point sampling, water features (river, stream, intermittent river, lakes), vegetation (marsh, swamp, salt marsh), cultural features (settlements, buildings, roads, railways, airfields, airport, etc.), artificial features layers (dyke, levee, seawall, breakwater, training wall,...), port features, rocks, wrecks, obstructions, offshore installation, tracks, routes, lights, etc. Each feature is linked to a record in the feature table and may be also associated with an attribute, e.g., each sampling point location in this study contains two linkages, one linkage for the feature record and one linkage for the corresponding attribute or measured record in the table position.
2. The multi-disciplinary (non-spatial) database built in Microsoft Access following the relational constraints.

Some parameters, which feed the database are summarised briefly:

- Determination of the density distribution along a core evaluating the attenuation of gamma photons of an Americium²⁴¹ radionuclide source mounted on a computer driven vertical detection system. Calibration of the gamma bank is achieved first by evaluating the attenuation characteristic of a set of standards of the Guayas estuary and Estero Salado sediments, according to the rules of measurement theory.
- Obtention of x-ray images of the core interior showing contrasting density layers, sedimentary structures and a complete context of the sequences of accumulation.
- Identification of the different populations of sediments for interpreting their evolution in time and space. A multivariate analysis reveals to be an appropriate approach for this identification regarding the observed variability in sediment input.
- The exponential decrease of excess Pb²¹⁰ activity with depth, along the sedimentary column permits to evaluate the rate of accumulation of sediments.
- Specific surface (SS) and cation exchange capacity (CEC).
- Organic matter and carbonate content in sediments.
- Organic pollutants. Different stable organic pollutants are analysed: PCBs and organochlorine pesticides, Lindane, HCH, Heptachlore, Heptachlore epoxide, Aldrin, Dieldrin, Endrin, Mirex, Cis- and trans -Chlordane, DDT, DDE, DDD).
- Rheological (visco-elastic) analysis.
- Acoustic measurements. Identification of the layers' characteristics such as thickness, density, at the mud and semi-permanent beds, by combining measurements with echosounders working at central frequencies of 3.5, 12, 33 and 200 kHz. This technique, again, has to be calibrated for the expected acoustic response of the local estuarine bottom.
- Primary productivity, oxygen and BDOs.
- Activity of benthic bacteria.
- Atomic absorption spectrometry is used to analyse heavy metals such as copper, chromium, cadmium, zinc, manganese, mercury, lead.
- In situ measurements of flock size, density, and settling velocities.

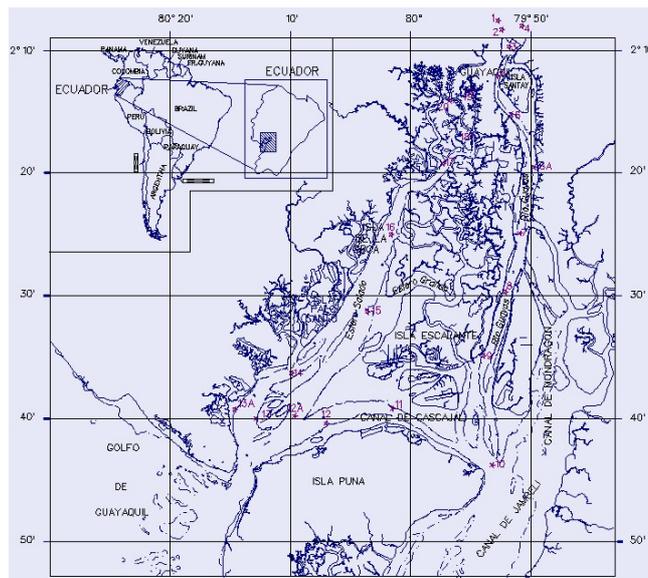


Fig. 1. Sample locations in the Guayas Estuary and the Estero Salado tidal channel in the vicinity of Guayaquil in Ecuador, South America

In total 156 different measurement parameters are stored in the GIS. Note that each station was sampled by tracks for epi-, hyper- and macrobenthos, for phyto- and zooplankton, and at anchor for meiobenthos, physics, chemistry and sedimentology at several depths at the water column, at the interface water-sediment, and at the bottom.

The data have been monitored during a normal-dry and a quasi-normal rainy season, with consideration of the tidal state and the vertical (depth) and longitudinal extent of the channels, along 22 stations located approximately in the middle of the channels (Fig. 1), together with navigation parameters from the sea cruise using the navigational package PC-NaviGIS developed by ELEC/Department (Vrije Universiteit Brussel) in association with TRESKO [4].

4. APPLICATION OF GIS IN SEDIMENT IDENTIFICATION FOR GEOTECHNICS BY MARINE ACOUSTICS (SIGMA) [5]

The European MAST-III SIGMA research project has been stimulated by new questions, which arise from the pollution of the environment and from large infrastructure constructions, which were erected on the continental shelf and in estuaries of industrialised countries or which are still under development. Concern about large infrastructure constructions, the characteristics of the upper few meters of the sea bed in terms of structure and type of sediments are furthermore of particular interest to industry and sciences for applications such as laying of cables and pipes, foundations for off-shore structures, investigating soil and slope stability, sediment migration studies, object detection, improving the accuracy of propagation modelling, relating sub-bottom properties to biological activity.

Therefore the aim of the SIGMA was to investigate the relations between the acoustic properties of marine sediments (reflection factor, sound velocity, attenuation, dispersion, etc.) and their geophysical and geotechnical properties (sediment type, grain size distribution, cohesion, gas content, etc.) obtained from instruments and equipment developed during the project. The aim was achieved by means of a multidisciplinary approach such as acoustic modelling, development of inverse procedures, calibration, generation of optimal test signals, system identification, validation by tank experiments, development of specific instruments, sea trials, sea data processing and archiving.

GIS has been integrated in the SIGMA project in order to provide an efficient and accurate means for collecting, managing and storing data in a attribute database, which allows the user to utilise highly diverse information sources to characterise and divide the marine environment into homogeneous sub-areas. The SIGMA GIS database has been designed for integrating and managing in single and integrated system historical, measured and graphic data.

The available graphic data (maps) used are those published in Lericolais [6] for the sites of Samdi (N49°45' to N49°52', W1°00' to W1°25'), Guernsey and Ombilic (N49°35' to N49°50', W2°30' to W3°10'), both located in

the English-French Channel. The spatial database that has been constructed contains the following geographical information:

- (1) The bathymetric spatial features are represented by depth contour lines (with attached depth values); the sampling station points and/or spot measurement points for which accurate geographic coordinates (longitude, latitude) have been measured or recorded with [D]GPS and the associated attributes as numerical fields, are represented by points (or measurement points), sometimes by text (label);
- (2) The navigational route lines derived from the SIGMA cruises ('Belgica 9826'). The CTD profile lines are represented by points and lines (see Fig. 2 and 3).

A structured SIGMA database has been built from the existing data and from the data supplied by the partners involved in the project. These data are stored as a collection of tables. Common fields in different tables are used to link them together to facilitate the interrelationship of multiple information layers.

Based on the data stored in the SIGMA GIS database, analytical operations can be performed, e.g., overlaying facilities on the above maps and database, selecting, querying and graphic display of result. The first sedimentological analysis on the existing historical data showed that the sub-bottom of the selected test sites for the first sea trial ('Belgica 9826') is composed mainly of sand, fine to coarse sand, sometimes mixed with gravel.

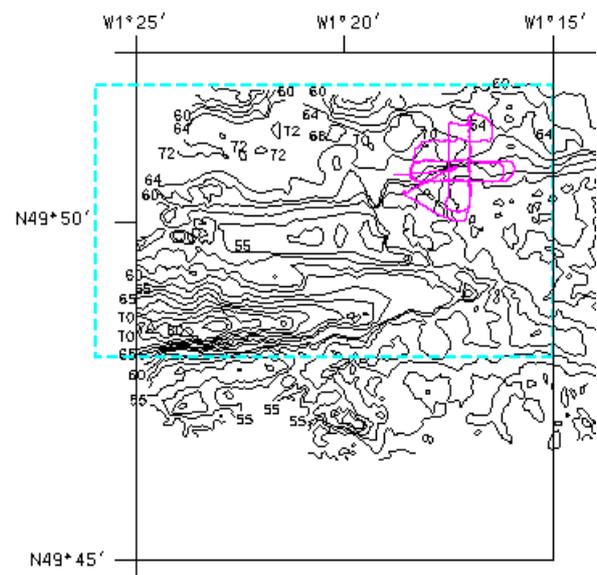


Fig. 2. An example of Derived SIGMA GIS Thematic Maps from the Sea Trials: Bathymetric map of survey area (Samdi) with vessel track (or navigation lines)

The surveys, conducted in the selected representative areas lead to the constitution of a well-controlled database (geo-referenced acoustic, geophysical and geotechnical information) on sea bottom sediment characteristics (Fig. 4). The system contains, besides geographical data from the sea trials and historical data from previous investigations, processed sea data obtained from instruments and equipment developed during the project. It provides search, retrieval,

distribution, and visualisation capabilities (producing maps of the selected test sites, Fig. 3-4).

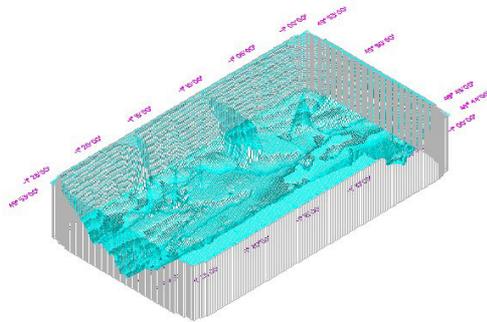


Fig. 3. A three dimensional (3D) map of the surveyed area derived from the bathymetric lines, produced using the TIN model approach.

As a result the Guayas-Salado environmental GIS database provides both spatial database referenced to specific locations on the earth and an attribute database, including date/time and depth, tied to spatial features. Therefore the analysis that is the ability to combine the basic data elements in the form of a question can be performed and is a complementary activity to data modelling, data visualisation and thematic mapping. This helps the user, planner and other to find the reasons behind the spatial pattern about the occurrence or the absence of some features where they are supposed to be. Note that this research project is actually followed-up by the development of a new alert system driven marine GIS for the sustainable management and development of the Guayas province. Forecasting of slides from El-Niño and diseases in shrimp pounds are examples of triggers for the alert system.

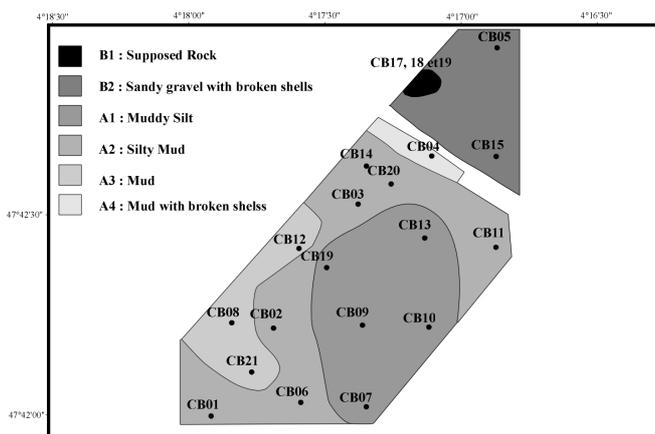


Fig. 4. Sedimentologic units of the surveyed area, as result of data analysis in the SIGMA GIS environment

5. CONCLUSION

From the discussions above, it is obvious that the GIS technology provides capability for some types of environmental crises that can be harnessed in environmental disasters management. The environmental marine GIS contains, indeed both spatial and temporal data, which allows forecasting from prognoses deduced from constructed time series and thematic maps. It allows analytical operations necessary to produce a set of thematic maps based on specific analytical queries in order to support monitoring, exploitation and sustainable environmental management of marine ecosystems.

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