Experiences in Applying Geographic Information Systems to Marine Conservation and Ecology in the Azores

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Abstract

Geographic Information Systems (GIS) are an innovative technology that allow for a geospatially structured and more interdisciplinary approach in a variety of marine science issues. The Department of Oceanography and Fisheries of the University of the Azores (DOP/UAç) has been using GIS in the scope of ecologic and conservation research of marine and coastal environments. The aims comprehend the production of graphical displays of marine and coastal datasets, support of zoning decisions by planners, and spatial analyses and modelling for improved interpretation of marine patterns and processes. Three examples are briefly presented illustrating the progress of these applications and how information from a variety of sources has been gradually integrated and geospatially intersected under a common framework. These cases relate to production of proposed management plans for Natura 2000 sites, modelling of cetacean habitat and high-resolution mapping of benthic habitats.

Some issues faced by GIS practitioners while working with marine datasets are pointed out encouraging future developments in the area, namely further integration with remote sensing packages and efficient handling of data-rich layers. Importance of making data more widely available as well as metadata and archive standards is also highlighted in face of the need for a wider digital dissemination and exchange of marine-related information in accurate and manageable formats.

Key-words: GIS; marine and coastal applications; modelling; protected habitats and species; Azores.

Resumo

Os Sistemas de Informação Geográfica (SIG) constituem uma tecnologia inovadora que permite uma abordagem espacialmente mais estruturada e inter-disciplinar numa série de aspectos das ciências marinhas. O Departamento de Oceanografia e Pescas da Universidade dos Açores (DOP/UAç) tem usado esta ferramenta no âmbito de investigação ecológica e de conservação de ambientes costeiros e marinhos. As finalidades abrangem a obtenção de visualizações gráficas de séries de dados marinhos e costeiros, o apoio a decisões de ordenamento e a execução de análises e modelos espaciais que permitam interpretações mais avançadas de padrões e processos marinhos. São sucintamente apresentados três exemplos que ilustram o avanço destas aplicações e a forma como informação de origens diversas foi gradualmente integrada e intersectada geospacialmente numa base comum. Estes casos relacionam-se com a produção de propostas de planos de gestão para sítios da Rede Natura 2000, a modelação de habitats de cetáceos e o mapeamento de habitats bentónicos a escalas finas.

No sentido de incentivar desenvolvimentos futuros na área, é dada especial atenção a algumas dificuldades enfrentadas por utilizadores de SIGs marinhos, nomeadamente a necessida de uma integração melhorada com pacotes informáticos de detecção remota e uma manipulação mais eficaz de conjuntos de dados densos. É salientada a importância de desenvolver padrões de meta-dados e de arquivo face à necessidade de uma maior divulgação e troca electrónica de informação relacionada com o mar em formatos exactos e geríveis.

Palavras-chave: SIG; aplicações marinhas e costeiras; modelação; habitats e espécies protegidos; Açores.

Resumé

Les systèmes d'information géographique (SIG) constituent une technologie innovatrice qui permet une approche géospatiellement structurée et interdisciplinaire dans une variété de domaines des sciences marines. Le Département d'Océanographie et Pêches de l'Université des Açores (DOP/UAç) utilise cet outil dans un but appliqué à l'étude écologique et la conservation des environnements marins et côtiers. Les objectifs poursuivis comprennent la visualisation graphique de données marines et côtières, l'aide à la mise en place de plans de gestion du territoire, ainsi que l'analyse spatiale et la modélisation des schémas et processus marins. Nous présentons succinctement trois exemples qui illustrent l'état d'avancement des technologies SIG et la manière dont des informations de sources diverses ont été graduellement intégrées et entrecroisées géospatiellement dans un cadre commun. Ces exemples sont liés à la proposition de plans de gestion pour des sites Natura 2000, à la modélisation de l'habitat des cétacés et à la cartographie fine des habitats benthiques.

Une attention spéciale est portée sur certains problèmes auxquels sont confrontés les utilisateurs de SIG travaillant sur des séries de données marines, dans le but d'encourager de futurs développements dans ce domaine, nottament une intégration ameilleurée avec des logiciels de télédétection et une manipulation plus éfficace de grands jeux de données. Il est également mis l'accent sur l'importance de développer des normes de meta-données et d'archivage permettant de rendre les données plus largement disponibles et de faciliter la diffusion et l'échange électroniques d'informations sur la mer dans des formats exacts et maniables.

Mots-clés: SIG ; aplications marines et côtières ; modélisation ; habitats et espèces protégées ; Açores.

1. Introduction

Geographic Information Systems (GIS) have been a common designation for software suites that are used for handling, displaying, analysing, and modelling information about the location of phenomena and features on the Earth's surface (Goodchild, 2000, xiii). For many years, they remained a land-locked ground-based technology as information for the essentially-2D land surface was much easier to collect and widely available than that about the dynamic 3D underwater world.

Growing demands for integrated management appraisals and decision-making in coastal and marine regions change this situation by producing geospatial databases about marine themes and making GIS steadily expand into the oceans.

Marine researchers have accompanied the interest in GIS since a spatial reasoning and the collection of geo-referenced data about oceanographic phenomena and marine features has been part of their methodologies since the early times anyway. However, they have faced several challenges that are not only technical but also conceptual (Wright, 2002: xix).

The problem most commonly referred is the lack of support of standard GIS for dealing with multidimensional datasets (e.g., Raper, 1999: 129). Oceanographic datasets are commonly four-dimensional (i.e. latitude, longitude, elevation/depth and time) and furthermore, multiple attributes may exist for each depth and time interval. This is an obvious processing challenge for a technology that was founded on the assumption that the two dimensions are horizontal and essentially equivalent and that representations are rotationally invariant (Goodchild, 2000: xiv).

The continuous movement of the waters also adds in significant complexity to the representation of geographic marine data (e.g. Lucas, 1999: 53). Ways of refreshing the information are required if an updated meaningful view of the dynamic marine realm is to be obtained. In the case of pelagic environments, traditional concepts of landscape measures such as patch area, habitat diversity indices and connectivity indices may not adequately describe ecologically-relevant ever-changing marine features, making hard to evaluate the suite of controlling factors involved in marine habitat quality, population dynamics, and consequences of environmental changes (e.g. Treml et al, 2002: 20). Even at the coast, there is very little of a static nature of features at the shoreline, since indicators of pattern at the sea-land interface are dependent on the degree of connectivity between the upland and the subtidal zones, which vary at multiple spatial and temporal scales, namely with the tidal regime (Goodchild, 2000: xii; Bartlett, 2000: 11).

Another important constrain is the lack of understanding of some biological, physical and chemical patterns and processes in the marine environment. This fact limits data manipulation as some procedures used for terrestrial data are not valid for marine data varying spatial and temporally. Often no alternatives are widely available in GIS packages.

Notwithstanding these issues, significant practical outcomes emerged during the last 15 years (Valavanis, 2002: 1) chiefly in applications that could make use of existing GIS frameworks.

The proliferation of technical know-how and advances in technology certainly made their contribution as well. The most important developments seem to have been: (i) the ability to perform remote sensing of ocean environments in unprecedented scope, speed and detail, (ii) the increase in computer power to analyse, interpret and disseminate the information and (iii) the introduction of critical developments in processing and database software to cope with more complex marine-based questions.

As a result, GIS gained wider acceptance and became a fundamental tool for marine and coastal research (Wright, 1999: 2-7) with multiple valuable applications both in the benthic and pelagic realms.

As a major marine research centre located in an archipelago with an attached EEZ (Exclusive Economic Zone) sub-area of almost 1 million square kilometres, the Department of Oceanography and Fisheries of the University of the Azores (DOP/UAç) has been involved in various research projects making use of GIS capabilities to analyse biological and ecological issues related to the sea and coast. Collection, assembly and processing of baseline information of a marine geographical nature are daily tasks at DOP/UAç and have been used to inform planning, conservation and management decision in the region.

The present paper provides three examples illustrative of the way GIS is being applied to study marine environments in the Azores. The case studies selected portray the gradual expansion of the information incorporated in the GIS environment, the problems encountered at works of different scale, the merging of study results from different DOP/UAç working groups and the evolution towards a unified scientific information management regime using GIS as a modelling framework. Objectives, methodologies, tools, and results are presented.

2. Case Studies

Three applications of GIS developed at the Department of Oceanography and Fisheries of the University of the Azores (DOP/UAç) are presented. The case studies illustrate uses of the technology in issues of conservation of marine habitats and species and do not intend to cover all of the subjects in which GIS have been used at DOP/UAç (namely the ones in the fisheries and physical oceanography sections).

Case-studies are presented in order of project kick-off and have been developed over the past 6 years by using the proprietary package ArcGIS Desktop (versions 8.x to 9.0). ArcGIS extensions such as Spatial Analyst, 3-D Analyst, Geostatistical Analyst have been extensively used to produce bathymetric surfaces and contours based on various interpolation methods, as well as to compute sea-bottom slope and to obtain statistics from raster grids representing relevant marine environmental variables. ArcScene module was used to visualise and explore DEMs. Scripts (freely available from the internet) provided additional help for several functions that have either more indirect solutions or cannot be conveniently accomplished with out-of-the-box ArcGIS interface, namely Hawth's Tools, ETGeowizards and XTools.

2.1. Mapping of Natura 2000 sites and zoning of marine protected areas

The commonly named Habitats and Birds Directives are the two prime pieces of European legislation relating to nature conservation. Both of them include requirements for the designation of conservation areas. In the case of the Habitats Directive these are named Special Areas of Conservation (SACs) and are set out to support certain natural habitats or species. Those deriving from the Birds Directive are called Special Protection Areas (SPAs) and protect wild birds of European Union interest. These two sets of sites will form a European network of protected areas to be known as Natura 2000.

Since the lists of SPAs and SACs were agreed for the Macaronesia biogeographic region, a series of projects (Life-Aves Marinhas, Life-MARÉ, OGAMP, MARMAC) have focused on them. Throughout these projects, natural features were assessed, socio-economic context was characterized and management proposals were elaborated. These have covered both the marine SACs and seabird-related SPAs and the regional directorates for fisheries and for the environment as partners.

During the course of these actions, GIS were first introduced in DOP as an every-day tool.

The main work developed in the aftermath of a 90-hour introductory course taught in 2000 by GIS experts and experienced technicians from the National Geographic Information Centre (CNIG). This event triggered the interest in GIS, improved and consolidated theoretical and practical know-how and tuned in various local working groups and institutions into a common language.

The most important tasks during these early stages of GIS implementation were the familiarisation with the software along with the assembly, treatment and addition of layers. Basic thematic layers were collated at this point from sources such as administrative bodies that were partners in the projects. Other were produced from own georeferenced data that were put into a GIS format and vectorial info was digitized from relevant scanned paper sources. Some Microsoft Excel databases were reworked from a geographical perspective and converted into a Microsoft Access format. Tables of interest were exported as .DBF and integrated in the GIS environment.

While bringing these data together, a common topic was ensuring that they bore accurate projection information, in order to guarantee their geographic correctness and the possibility to correctly transform them into new coordinate systems, when it was necessary.

A Universal Transverse Mercator (UTM) projection and the regional data of São Braz (for the eastern island group), Graciosa SW (for the central island group), and Observatório Meteorológico 1939 (for the western island group) ended up as the most commonly used in the GIS projects as they were the ones born by the majority of the layers.

Since the areas of interest were both coastal (seabird-related SPAs) and marine, nautical charts were integrated in the GIS. Analysis of the bathymetric charts, namely the assessment of the strata covered by the designated area, is a key element in understanding and delineating the range of habitats within the marine SAC (Bates & James, 2002: 38). In the absence of digital data, published charts of several scales had to be scanned and geo-referenced. Vectorial features of interest were digitized as polygons (e.g. islands), lines (e.g., depth contours, coastlines) or points (scattered soundings and bottom types). These were used mainly to generate digital elvation models (DEM) by producing regular grids and triangulated irregular networks (TINs).

Because topographical and bathymetric data have been historically mapped by different institutions with distinct methodologies and perspectives, the coastal interface was a problematic area to work in as data do not coincide in scale and in datum. Topographical data are typically UTM and referred to the Mean Water Level vertical datum, whilst bathymetry information is typically in Lat/Long coordinates and reduced to the Hydrographical Chart Datum.

Due to the microtidal regime in the Azores, the difference between the two vertical data is of less than 2 meters. The broad scale of the work and the fact that most of the coast is rarely gentle sloping, contributed to minimize the degree of imprecision related with stitching that had to be done to produce continuous maps. It is however worth-mentioning that this gap does not seem to be detailed neither in topographical nor hydrographic maps.

The main outcomes of these GIS projects were on-screen visualisations and production of graphic outputs for reports.

Maps produced in a GIS environment illustrate the reports depicting interpreted extension of biological assemblages (e.g., Tempera et al, 2001a: 4), scattering of the scuba diving surveys, extension of human activities (e.g., Ferraz et al, 2004: 26) and spatially explicit boundaries recognisable by users and enforcement authorities (e.g., Tempera & Santos, 2003: 5).

The proficiency of GIS in presenting different types of data complementing each other in a common environment was instrumental in the assignment to define fine-scale practical limits for the coastal and marine Natura 2000 (see Anonymous, 2004). This was delivered both in the form of digitized vectorial layers (with attribute tables populated with information such as name, designation code, area or species occurrences) and exhaustive written descriptions (based on examination of ortho-rectified airborne photography and vectorial layers portraying information such as existing infra-structures, roads, waterways, land use, topography and bathymetry). Area calculation tools were very useful for the development of this task as a set of geospatial guidelines had been established a priori for its completion. The compliance with the areas of individual SACs and SPA published in the legislation and a maximum deviation from these values were among the primary ones, along with the use of easily recognisable forms of limitation on land and sea.

In the case of the marine SACs, which present extension was deemed as too restricted to effectively protect some of the features to be maintained (Tempera et al, 2001b: 62), GIS were particularly important in analysing potential expansion of the protection beyond the designated areas and establishing zoning schemes within them. An informal public hearing of Corvo island interest groups was largely based on GIS maps depicting the alternative zoning schemes and locations of traditional fishing grounds pointed out by local fishermen (Cardigos & Tempera, 2004: 3). This fusion of information aided the interpretation of spatial relationships and perception of potential conflicts. A final zoning proposal was achieved that was informally reckoned by the local population as acceptable and considered by the scientists to be compatible with the conservation objectives and conservation of core features.

2.2. Distribution and Habitat Preferences of Cetaceans in the Waters around the Azores

The great diversity of marine mammal species, coupled with a relative ease of observing many deep water species close to shore due to the absence of a continental shelf (Silva et al, 2003: 82), makes the Azores archipelago a privileged area for cetacean research. Moreover, the increasing social-economic interest of this group – resulting from an historical whaling past and a very active present whale-watching scene – urges the development of biological and ecological studies that may scientifically inform management decisions.

Spatial analysis of cetacean-habitat relationships is technical and conceptually challenging due to (i) the complex nature of the animals themselves and (ii) the vast extent and dynamic nature of the oceanographic environment. Discernment of distribution patterns of marine mammals is confounded by the fact that some species can spend 90% of their time underwater (Schick, 2002: 80). A fundamental understanding of ecology is required and environmental variables (or proxies) representing hypothetically relevant oceanographic features have to be identified. As far as is it known, cetacean distribution is often primarily influenced by prey distribution (Cañadas et al, 2002: 2053 and references therein). In turn, this is influenced by ocean features such as water temperature and bathymetry (e.g. Baumgartner et al, 2003: 137). Alongside scale-related issues have to be taken into account (e.g., Gregr & Trites 2001: 1282). These are important at several levels, since not only the scale of the question and the scale of the available data are easily mismatched, but also the scales at which the animals resolve the world are stochastic and dependent on the opportunities and constrains imposed by their surroundings.

Until recently, studies of cetacean distribution in the archipelago largely relied on opportunistic sightings, strandings, catch data from the whaling era or limited survey data (for a review see Santos et al, 1995: 334). While these earlier studies provided some insights on the occurrence of cetaceans, the ecological mechanisms acting on the distributional ecology of populations along the archipelago remained undetermined. Presently, cetacean studies are one of the main research lines at the Department of Oceanography and Fisheries of the University of the Azores (see project CETAMARH at http:// www. horta. uac. pt/projectos/cetamarh/). GIS provide a single framework in which geo-referenced field data is overlaid with environmental datasets for the study region to characterize cetacean habitat (Fig. 1).

Field data consisted of geographical positions of groups of cetaceans observed and of transect route locations, both obtained through GPS, during boat-based surveys conducted for a period of six years (1999-2004) in the waters around the Azores islands. Location of sightings of each cetacean species were introduced into the GIS project as point themes with associated tables of attributes containing complementary information about date, time, sea state, weather conditions, estimated number of individuals, group activity, behaviour and group composition.

Visualization of simple overlays of sightings with environmental data would be misleading because the distribution of sightings of cetacean groups is also influenced by the execution of more or less survey effort in each area.

Therefore, transect routes were integrated as a vector layer and the study region was divided into 1x1 nautical mile (nm) squares. Sampling effort was then measured as the distance travelled in each square with adequate sighting conditions.

GIS display was used throughout to detect inconsistencies such as sightings out of the sampling area or boat routes crossing land masses. Editing utilities permitted the geographical correction of such inaccuracies.

An encounter rate (ER = number of sightings per 100 kilometres searched) was then calculated for each square intersected by a transect line. ERs were computed separately for each species across several temporal scales: the whole period of study, yearly, seasonally and on a monthly basis (within each year). This computation resulted in grids of abundance per unit of effort (Fig. 2). Model builder, one of the geoprocessing ArcGIS 9.0 developments, was crucial to organizing all the necessary multiple queries and relational links from the three baseline layers – 1nm grid (polygons), sightings (points) and transects (polylines) – to obtain the final calculation of ER index for all species, and for all the time periods considered. Sequences of steps for selecting and intersecting feature classes, performing consecutive table joins, adding and calculating fields and extraction of new layers were all facilitated by running processes built from tools contained within the system toolboxes and customized in appropriate order to perform multiple operations at once.

Distance to coast, physiographic (depth, slope) and oceanographic (sea-surface temperature) data were assigned to the centre of each 1 nm square. Bathymetry was obtained from a digital dataset (1 minute resolution) and sea-bottom slope was computed as the gradient of maximum change in depth (0°-90°). A "distance from shore" layer was generated using the Euclidean distance to the nearest point of land for each sighting location. High-resolution (1.1 km x 1.1 km) sea surface temperature (NOAA Advanced Very High Resolution Radiometer) and chlorophyll concentration (SeaWIFS) derived from satellite measurements for the period of 2001-2004 were used to produce a set of monthly composite images in IDL software (see http://www.horta.uac.pt/projectos/detra). These images were processed and integrated in a GIS database but not without going through fastidious processes of format conversion and geo-registration.

After the import into the GIS environment, monthly synoptic satellite images still required some raster processing. Programming skills were used to design specific computation procedures and guarantee an efficient handling of the large number of data-rich images. Under the scope of a research exchange with the University of Rhode Island, AML (ARC™ Macro Language) scripts were prepared and run in ArcInfo Workstation (ESRI software ®). Looping through the several images files they performed a sequence of coherent procedures including (i) application of a mask for the islands area, (ii) setting of "no-data" for zero values representing cloud cover and (iii) low-pass filter to reduce high frequency and high wave number variability (by applying a focal median through a 3x3 pixel running window).

Throughout this underpinning stages GIS tools were also instrumental in supporting procedures such as definition and transformations of projection systems, integration and management of features classes in a common geodatabase, raster-grid manipulations, conversion of data models (raster to/from vector) and computation of distance, counts and area.

Depth, slope and the closest distance to the shore associated were determined for each sighting based on geographical location. Exact values of SST and chlorophyll concentration were obtained by intersection with the synoptic image closest to the date and time of each sighting.

While spatial associations of cetacean distribution with static physiographic variables (namely depth and slope) could be readily perceived from map displays, the same was not true for associations with SST and chlorophyll concentration maps. High time and space variability of these oceanographic parameters around the Azores precluded the perception of any patterns.

To conduct quantitative habitat analyses, traditional statistical approaches are typically simple correlations, chi-square analysis, formal multiple regression models or discriminant function analysis. GIS packages do not provide these statistical tools required for habitat analyses, making exportation of data to separate statistical or analytical software necessary. In this study, geodatabase tables of relevant layers were loaded into a statistical program where hypotheses about habitat preferences were tested and a regression model was built for each species to relate environmental variables with cetacean distribution. Depending on the data available for each species, general linear models were used for data of relative abundance (i.e. encounter rate) or logistic models were chosen when considering presence/absence.

Preliminary results showed that patterns of habitat selection and high-use zones are indeed related to local physiographic and oceanographic characteristics, revealing species-specific ecological requirements. From the results of the multiple regressions models fitted to the data, predictive maps of probabilistic spatial and temporal distributional patterns of cetacean habitats as a function of the significant environmental variables were obtained and compared with the observed sighting locations (Fig. 3). In particular, predictive habitat representation can be shown both in a continuous form (by which the gradient of environmental suitability for a certain species is reflected over the study area) or in a discrete/categorical manner (e.g. suitable vs. non suitable, defined by a threshold value of environmental suitability).

Another important fact is that spatially-explicit implications of model predictions could be easily explored in the GIS environment, aiming to highlight the importance of certain areas for conservation and to contribute to a better management of critical habitats for cetaceans in the Azores. Although the limitations of a prediction model are numerous, simple visual inspection of resultant maps can provide a context for interpreting eventual anthropogenic influences on cetacean's distribution. Thus, spatial overlap of probabilistic distributions with polygons representing locally protected areas as well areas of possible danger might be useful (e.g. Engleby, 2002: 57). This method is being used in the present study, namely by looking at the proximity of high-use areas of coastal dolphin species relatively to several Special Areas for Conservation or when proposing a decentralization of the whale-watching operational area. The ideal habitat model should be able to function over a range of space and time scales, making predictions for non-surveyed areas of the archipelago, allowing future inclusion of other dependent and predictor datasets, and providing a potential to predict eventual effects of environmental shifts and man's activities on the occurrence and distribution of cetacean in Azores.

In conclusion, with the adoption of GIS, learning where a marine mammal is located and the possible factors that regulate its location have become simpler, since cetacean-environment associations can be discerned and powerfully analyzed. GIS is useful to provide much more than simple "snapshots" of cetacean sightings, since information on preferred habitats and seasonal movements can be gleaned and predictions can be visualized. In the future, this GIS-based approach is expected to serve as a foundation to link the different aspects of cetacean research at DOP/UAç, including photo-identification, behavioural, genetic, energetic and habitat data by using unified spatio-temporal attributes.

2.3. Mapping of Marine Habitats in Faial island and neighbouring channel to Pico

Hard seafloor habitats (also known as reefs) concentrate most of the conspicuous marine biodiversity and of the demersal fishing effort in the Azores. Among the species that directly depend on them for either the whole or part of their life cycles are a variety of benthic macroalgae, invertebrates and demersal fish that are important both for economic and/or ecological reasons.

Being aware of this DOP/UAç has concentrated a large segment of its research on hard bottom species, assemblages or biotopes. The knowledge acquired has been relevant not only for scientists but also for managers and decision-makers. Mapping these habitats and stydying the species associated with them will allow for enhanced management measures and more accurate designs for the areas aimed at protecting biodiversity and essential habitats for species of commercial/touristic interest.

In contrast with what happens on land, widely-available and large-coverage sources such as satellite and air-borne imagery are of limited use for mapping of marine habitats [see Green et al (1996), or Mumby & Edwards (2002) for a more recent update on the subject]. This is because electromagnetic energy normally used for obtaining imagery through the atmosphere does not propagate well through water and therefore habitat discrimination from these types of technology is generally restricted to clear shallow waters (generally <25m deep) displaying explicit boundaries from surrounding environments.

Shipborne acoustic techniques are used instead, as sound is the only form of energy that travels efficiently in the water. Often this involves a dedicated mobilization of scientific and technical crews in boats to perform costly missions at sea. In studies requiring the collection of fine scale data, partnerships among institutes may also be required as some of the modern large-area coverage technologies are still not widespread among research centres in all countries.

This present case-study is ongoing and aims at the characterisation, classification and predictive modelling of the distribution of benthic assemblages in the sublittoral rocky habitats of the shelf of Faial island and neighbouring channel to Pico.

Collecting and processing the data has involved collaboration of DOP/UAç with partners such as Institute of Systems and Robotics (Portugal), Cardiff University (Wales) and University of St Andrews (Scotland). The work comprises (i) missions at sea to collect physical data for characterizing the geomorphology and oceanographic regimes around the islands (ii) scuba diving and remote operated vehicle (ROV) deployments to groundtruth acoustically-identified seafloor typologies and characterize the benthic assemblages (iii) integration and derivation of datasets in a GIS environment to generate matrices of biological occurrences vs. environmental parameters (iv) statistical analysis to analyse the primary factors regulating the spatial distribution of the species on an island scale and the assemblages they compose, and (v) establishment of statistical models for predicting and mapping the spatial distribution.

GIS plays an important role at several steps of the study. The initial use was for preparing the survey work. Visualisation of positions of previous samplings gathered from literature reviews and previous projects in the area provided a comprehensive view of what was known already for the study area.

As more data were gathered more layers were integrated in the GIS project which has been used to inform subsequent sampling tasks. Seabed physiographic types digitized from backscattering imagery, for instance, were used in improving the stratified sampling design and resulted in a more efficient placement of the samples of biological assemblages (either through ROV or scuba dives).

Concurrently, maps of surficial seabed character and features aided the decision on where to position buoys aimed at collecting information on currents within the channel and in neighbouring areas. Indications of scouring or strong mobilisation of sediments, as highlighted by sun-illuminated imagery, were used in tracing where the strongest bottom currents were probably taking place. The visualisation of the sort of bottom expected below the anchoring structure was also important in designing the lower part of the mooring (namely how far from the bottom the release would be put).

While surveying, GIS have also provided a significant aid. By importing the tracks performed by the boat during the acquisition of swathe data, an almost real-time crude assessment of the progress of data collection could be overlaid on base maps. This allowed for some shipboard decision-making on whether additional survey lines were required and where they should be located.

Uses of GIS extend to the post-survey stage as well. Overlaying of nearshore tracks, backscattering and bathymetrical data with fine-scale vectorial layers of coastlines have provided a quick quality control method for assessing navigation errors. Rasterized results from distinct bathymetry surveying methods (interferometry, multibeam and published charts) have also been compared in a GIS environment.

By allowing the overlay of the groundtruthing information (e.g., data on bottom type assembled from grabs, ROV, scuba-diving and nautical charts) with the backscattering imagery, GIS have also facilitated the interpretation of acoustic remote sensing and the digitizing of vectorial layers such as habitat type polygons (Fig. 4).

Merging the bathymetry data acquired from the interferometric and multibeam surveys with supplementary points from published charts to cover data holes has been another service of GIS that allowed the production of continuous TINs and grids. The visualisation of DEMs joining the topography and bathymetry data has been an instrumental interpretation aid in exposing the links between the terrestrial and underwater geomorphologic structures (Fig. 5). One of the most relevant obstacles fond while doing this was the high data-richness of the bathymetry datasets acquired with the multibeam and swathe technologies. This is particularly true in shallow water data which density is often too burdensome to GIS. An option has been to import only binned data at lower resolutions that those the original data allow for. An alternative has been to employ other geospatial visualisation software such as Fledermaus (IVS ®), a fully interactive 3-D environment that supports the multilayer and geo-referenced aspects of GIS (Fonseca et al, 2002: 18) and is remarkable capable of handling fine scale graphical rendering and rapid changes in the scale of visualisation. This complementary tool has also been helpful in producing eye-catching DEMs and animations for dissemination purposes.

In the final step of this research, GIS will provide the geospatial means for the most interesting analysis: the modelling of the occurrence of benthic sublittoral species and assemblages. In order to do this, biological observations of species and assemblages will be spatially intersected with layers characterizing the variation of the environment factors expected to primary regulate their distribution on an island scale.

This requires a project conjugating the locations of biological sampling stations (with species and assemblage occurrences among the attributes) with geo-referenced layers generated from a series of sources, scales and software. The environmental datasets to include are: thematic maps of oceanographic regimes derived from synoptic satellite sea surface temperature (SST) and surface productivity imagery (Seawiff); fine scale bathymetry rasters derived from multibeam surveys binned/gridded at different resolutions; slope and aspect maps derived from fine scale bathymetric models; rasterized polygons of seabed physiographic types digitized from seabed backscattering imagery; raster produced by a swell exposure model (index) with a coastline node resolution of 100m and raster produced by the shallow water current model characterizing maximum near-bottom current velocity.

The tables of biological occurrences vs. values of the environmental parameters produced by the intersection will be exported and used to produce statistical models (e.g., generalized linear models) in packages external to the GIS environment.

At this point it is worth underlining that some of the environmental datasets are strongly based on modelling themselves (rather than on observational data). The latter aspect is particularly relevant for factors such as current strength and exposure to swell indexes, which coverage with direct observations is currently limited (in space and time). These surrogates require extensive interpolation and can only be scarcely validated. In these cases, error possibly creeps in since the phenomenon is not being measured accurately (von Meyer et al, 1999: 298). The disadvantage of this approach is acknowledged as such explanatory variables may display degrees of relationship with the response variables that are less significant than what could be obtained in ideal situations where models are based and validated by finer scale data.

After these models are developed, tested and matured, modelling formulae will be brought back into the GIS environment and 100% coverage predictive maps will be produced. GIS will provide depictions of the validity of the predictions by contrasting the latter maps with the observations used in the model as well as with new observations.

3. Final considerations

Though technically challenging, taking a spatial approach to marine ecology through GIS brings into play a more realistic and intuitive framework. This fact should increase the power and ease with which some geospatial observations can be interpret and the results obtained are expected to inform better management decisions of marine environments and its resources.

As described above, GIS are presently providing a powerful interactive tool for managing, displaying and cross-analysing data that can provide better insights on ecology issues concerning a series of Azorean marine and coastal habitats and species that are of conservation interest. So far the GIS-based research carried at DOP/UAç has included data digitizing and editing, synthesis of multidisciplinary datasets from a variety of platforms, production of publication-quality graphics and implementation of spatial analysis and modelling.

One of the major challenges in putting up marine-related GIS projects has been the scarce availability of even basic layers, such as bathymetry, coastlines representing the hydrographical chart datum, bottom types or administrative units such as the EEZ, territorial sea, or boundaries of marine protected areas. Virtually none of these is freely available from Portuguese websites which is extraordinary considering the importance of Portugal's socio-economic interests in the sea and the huge marine area under national sovereignty. The establishment of an internet-based atlas of marine and coastal geographic data is suggested as a contribution to alleviate this problem. Such a digital infrastructure should involve a multi-institutional collaboration and would assist managers, researchers, and the public in general by providing standardized geo-referenced data. A capability for online uploading new layers would be an interesting feature for this atlas that could ensure its continuous and trustworthy development provided some metadata standards were guaranteed.

Regardless of all the plethora of tools already accessible in a GIS environment, researchers characterizing the habitats of marine organisms have faced some of the technical limitations of current packages. One of them was the lack of integration of GIS with a number of software suites traditionally used in physical oceanography and remote sensing. Feeding of new data and updating of GIS displays while working with geodatabases and routine protocols has not been a trivial and straightforward task as external formats were seldom directly readable in ArcGIS. Further streamlining of data ingestion procedures is required since GIS will possibly never be able to perform remote sensing and statistics tasks and complementary software needs be used in association.

Three dimensional rendering of data-rich DEMs (such as the ones provided by the modern bathymetry surveys) was another drawback even in dedicated modules such as ArcScene. Finding a solution probably requires adoption of new software coding closer to the one implemented in packages such as Fledermaus.

At an institutional level, further integration in the format and design of databases used by different workgroups is also desirable if analyses using broader data resources are to be performed. Concurrently, the work needs to be continued on adapting historical and operational databases in order to make them promptly readable by GIS and allow geospatial information to be retrieved by specific queries. The production of synoptic oceanographic maps (e.g., raster datasets of temperature and ocean colour) also requires some restructuring as formats typically produced by remote sensing teams still require significant treatment before they can be imported or worked in a GIS environment.

A final challenge will be the adoption of metadata standards and procedures for data resulting from a wide diversity of techniques and software. Until a layer is finally ready to be imported into a GIS project, the original data go through many steps requiring a complex sequence of technical decisions. Computerized automated logging would be an interesting development, if uncomplicated quality control and widespread use are to be promoted.

In conclusion, the expansion of GIS use into the marine environment presented many similarities, but has also confronted GIS with many noteworthy dissimilarities.

In order to meet growing requests from marine scientists and managers current weaknesses must be regarded as stimulating challenges to Geography. Through an on-going adaptive process and continued convergence of effort into research there is a high probability these issues will be solved in the near future enhancing the usage of this captivating tool among marine sciences. In the meantime attention is required to avoid technology taking over the analysis due to lack of the most adequate solutions. Having clear goals and/or testable hypotheses from the beginning is crucial to prevent this happening.

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Figure 1. Overlay of survey positional data (i.e. cetacean sightings and sampling track-lines) with environmental datasets for the study region (bathymetry, slope, chlorophyll concentration and se-surface temperature, from top to bottom)

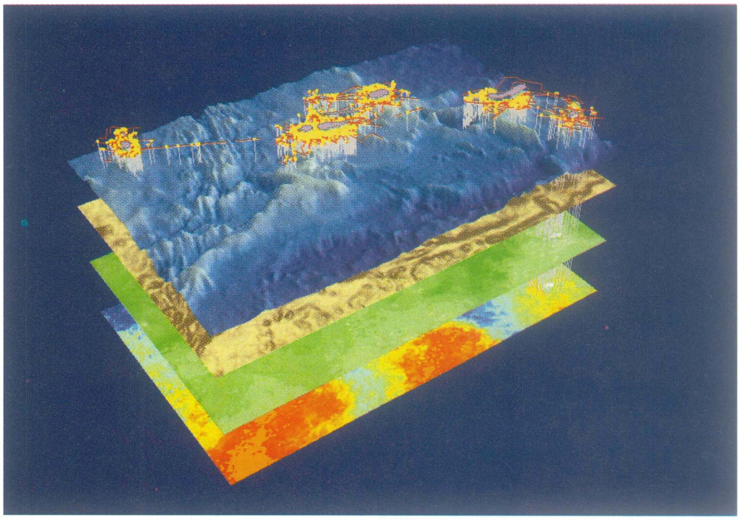

Figure 2. Example of a grid of relative abundance computed from sighting and sampling effort data for a given cetacean species in the Azores. Darker colours represent higher values of encounter rate.

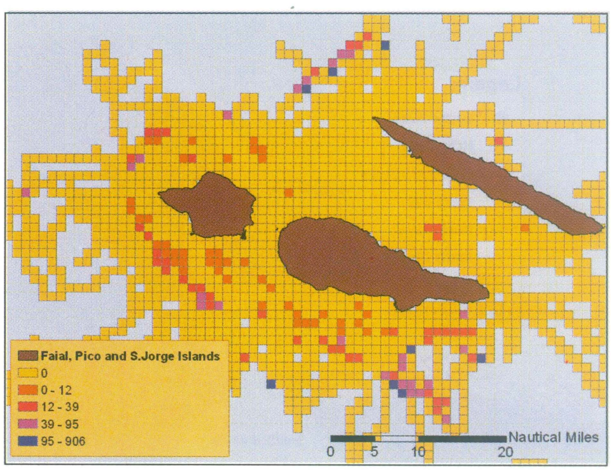

Figure 3. Example of a predictive habitat map for a given cetacean species in central Azores. Shaded areas depict probability of sighting presence (0 to 1) for sampled grid-squares from a logistic regression model constructed from survey data as a function of significant environmental variables.

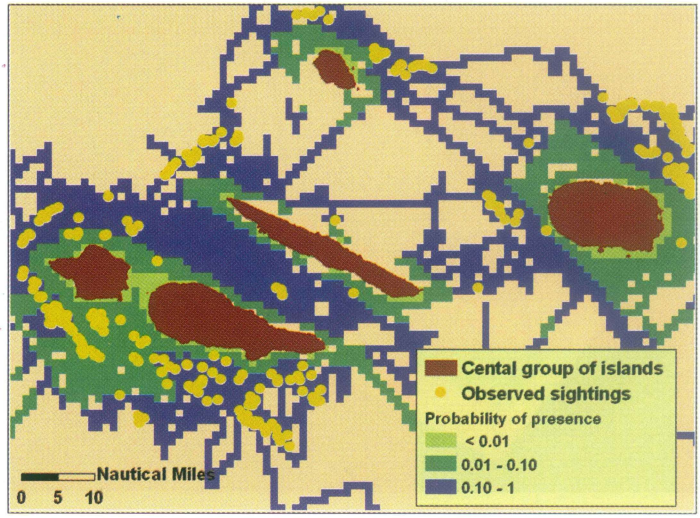

Figure 4. Overlay of datasets for point samples (scuba, ROV and grabs), swath survey tracks (lines), underlying bathymetry (rasters) and habitat categories (polygons) around Monte da Guia (Faial island).

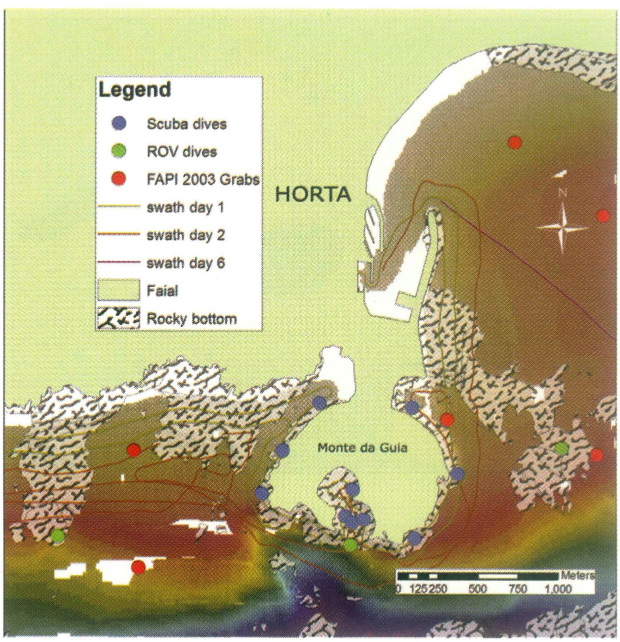

Figure 5. Shaded relief 3D plot of the topography and bathymetry of Faial island. Note the continuity of terrestrial and underwater features.