Epilogue

Spatial Reasoning for *Terra Incognita*: Progress and Grand Challenges of Marine GIS

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Introduction

"Just as fish adapted to the terrestrial environment by evolving into amphibians, so GIS must adapt to the marine and coastal environment by evolution and adaptation." — Goodchild (2000)

"Applying GISs to marine and coastal environments presents taxing, but particularly satisfying challenges to end users and system developers alike." — Bartlett (2000)

After many years of focus on terrestrial applications, an increased commercial, academic, and political interest in the oceans throughout the 1990s has spurred fundamental improvements in the toolbox of GIS and its methodological framework for this domain of applications. The adoption of GIS for ocean by agencies and institutes such as the National Oceanic and Atmospheric Administration (NOAA) National Marine Sanctuary Program and National Ocean Service, the U.S. Geological Survey (USGS), portions of the Woods Hole Oceanographic Institution, the Monterey Bay Aquarium Research Institute, the Nature Conservancy, and many others speaks to its growing utility not only for basic science and exploration, but also for ocean protection, preservation, and management (e.g., Convis, 2001; Breman, 2002; Wright 2002; Green and King, 2003a). Indeed, "marine GIS" has progressed from applications that merely

Wright, D.J. and Halpin, P.N., in press. Spatial reasoning for terra incognita: Progress and grand challenges of marine GIS, in Wright, D.J. and Scholz, A.J. (eds.), *Place Matters—Geospatial Tools for Marine Science, Conservation, and Management in the Pacific Northwest*, Corvallis, OR, Oregon State University Press.

collect and display data to complex simulation, modeling, and the development of new coastal and marine research methods and concepts (and the term marine GIS is used here to mean applications to the deep ocean, but also to the coasts, estuaries, and marginal seas, and by scientists and practitioners working as academic, government or military oceanographers, coastal resource managers and consultants, marine technologists, nautical archaeologists, marine conservationists, marine and coastal geographers, fisheries managers and scientists, ocean explorers/mariners, and the like). Numerous innovations in remotely sensed data (both satellite based and *in situ* acoustic), ocean sensor arrays, telemetry tracking of marine animals, hydrodynamic models and other emerging data collection techniques have been added to the information data streams now available to answer marine science questions. And the commercial GIS sector continues to pay heed to the needs of marine and coastal GIS users, with many of the leading vendors entering into research and development collaborations with marine scientists and conservationists.

The preceding chapters of this book highlight many more of the success stories of marine GIS. Common themes include new methodologies for data analysis and implementation of the science and policy underlying the siting and design of shoreline conservation and marine protected areas, improved synthesis of information for policy makers (particularly in map form), ways of incorporating local ecological knowledge and socioeconomic concerns, and ways to more effectively communicate the complexity of the marine realm to the general public. A common language of practice is developing for marine conservation GIS at many geographic scales from ocean basins to local marine habitats, while at the same time some distinctions still present challenges (such as the definitions of “habitat” and the varying ways of representing and analyzing benthic terrain in this regard, from measures of “benthic complexity” to rugosity to position indices).

It is the purpose of this chapter, however, to briefly review some longstanding challenges, challenges that underpin the successes of many of these applications but continue to provide avenues for further study, especially for posing important questions about the representation of spatial and temporal information in the marine environment (a marine GIS research agenda of sorts). In one way, the commercialization of GIS as a black box tool in the 1980s had the long-standing, beneficial effect of making GIS accessible to users who did not need advanced training in computer programming. But from an information technology perspective it may also have had the detrimental effect of limiting the research into the underlying data structures and algorithms. To wit, most papers at GIS conferences during this time dealt with research using GIS; far fewer dealt with research on the information system itself, the data structures and spatial analysis algorithms, and innovative approaches to the integration of data, models and analysis for use in scientific hypothesis generation, prediction, and decision-making.

In the 1990s the advent of geographic information science (GISci), the “science behind the systems,” and the organized leadership of groups such as the National Center for Geographic Information and Analysis (www.ncgia.ucsb.edu) and the University Consortium for Geographic Information Science (www.ucgis.org) changed this dramatically, where questions of spatial analysis (special statistical techniques variant under changes of location), spatial data structures, accuracy, error, meaning, cognition, visualization, and more came to the fore (for the most comprehensive treatment of GISci see Longley *et al*., 1999). Pursuant to GISci is the notion of “spatial reasoning,” first defined by Berry (1995) as a situation where the process and procedures of manipulating maps transcend the mere mechanics of GIS software interaction (input, display and management), leading the user to think spatially using the “language” of spatial statistics, spatial process models, and spatial analysis functions in GIS (Fig. 13.1). This has been an important concept for the oceanographic community to embrace, as many have seen the utility of GIS only for data display and management (e.g., Wright 2000).

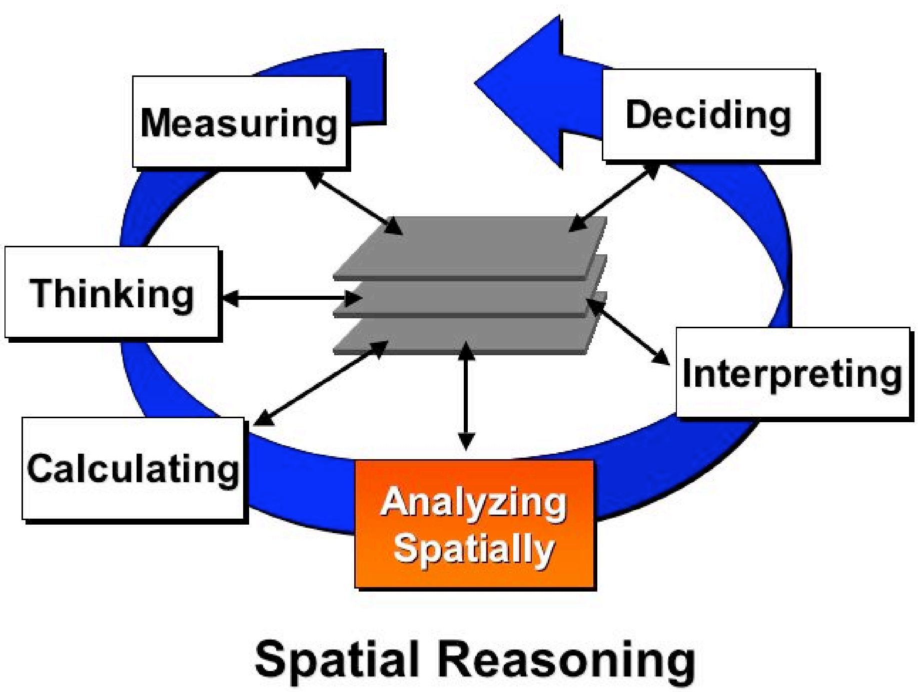

Figure 13.1. Illustration of the process of spatial reasoning, where the mechanics and issues surrounding the gathering and processing, and mapping of data in GIS lead the user to better understand and interact in the spatial “language” of GIS (rudimentary spatial analysis, spatial statistics, spatial process models, etc.). Modified from an Environmental Systems Research Institute (ESRI) GIS Day diagram.

For the coast and oceans it is clear that the use GIS is now crucial but, its use in this challenging environment can also help to advance the body of knowledge in general GIS design and architecture (Goodchild, 2000; Wright and Goodchild, 1997). The next section highlights a key motivation advancing the development of geospatial technologies: the need for more precision in marine resource science and management, followed by a brief review of current challenges of marine GIS in terms of: (1) data access and exchange; (2) spatial and temporal representation, and (3) the need for more temporally dynamic analytical models. These are discussed within the context of the benthic habitat, marine fisheries, and conservation focus of this book. Note that there is additional, detailed background on these challenges in Li and Saxena (1993), Bartlett (1993a and b), Lockwood and Li (1995), Wright and Goodchild (1997), Wright and Bartlett (2000), and Valavanis (2002).

Motivation: The Rapidly Increasing Demand for More Precision in the Management of Marine Resources

In direct parallel with developments in terrestrial natural resource management, managers and scientists are now being tasked with answering increasingly precise questions concerning physical, biological and social resources of our coastal and marine environments. In the terrestrial realm, geospatial technologies (GIS, global positioning system, and remote sensing) have been widely and increasingly applied to assist in the “precision management” of agriculture, forestry, urban planning, business and national defense issues. The application of geospatial technologies to terrestrial resource management has fueled a revolution in the process and practice of resource management. Farmers, forester's urban planners and business owners now regularly use geospatial technologies to optimize the management of their resources across a wide range of scales.

There is now emerging an equally strong demand for "precision management" of coastal and marine resources. The coastal and marine science and management community are challenged daily with increasing demands for more detailed analysis of the physical and biological processes. The coastal and marine community, however, faces additional challenges in the application of geospatial technologies. The three dimensional nature of the marine domain, the temporal dynamics of marine processes and the hierarchical interconnectedness of marine systems grossly increase the complexity of developing and applying geospatial solutions to marine management questions.

For example, the development of effective marine protected areas or time-area closures require scientists and managers to explicitly and precisely assess resource usage and potential conflicts in both space and time. The idealized goal of developing "win-win" management plans that optimize for both sustainable resource use and biological conservation will require an exceptionally high level of precision to ensure that economic and conservation resources can be separated in both space and time. Precision (as well as accuracy) in the delineation of the boundaries of these areas is a challenge (e.g., Treml et al., 2002), as they often transcend federal and state jurisdictions and may extend to the seafloor or into the subsurface. Descriptions of regulatory boundaries often are subject to misinterpretation (i.e., are imprecise), and if jurisdictional disputes arise, conservation and sustainability goals may be delayed or compromised.

In addition to the emerging challenges of precision management for marine practitioners is the vast quantity of data that are necessary for assessing, modeling and monitoring our coastal and marine environments. A recent report assessing the geospatial data needs of the Integrated Ocean Observing System (IOOS; Hankin et al., 2003), estimated that the annual data flow of oceanographic data collected to support this effort will exceed ~2.9 terabytes per year.

In addition to the rapidly proliferating quantity of coastal and ocean data, much of the geospatial analyses that will be needed to be conducted in order to support scientific and management programs will require the fusion of multiple sources of physical, oceanographic, biological, fisheries and management datasets together. In order to seamlessly merge data from disparate sources together, significant development will need to occur in the advancement of data dissemination tools, data standards, data transport protocols and Internet collaboration tools.

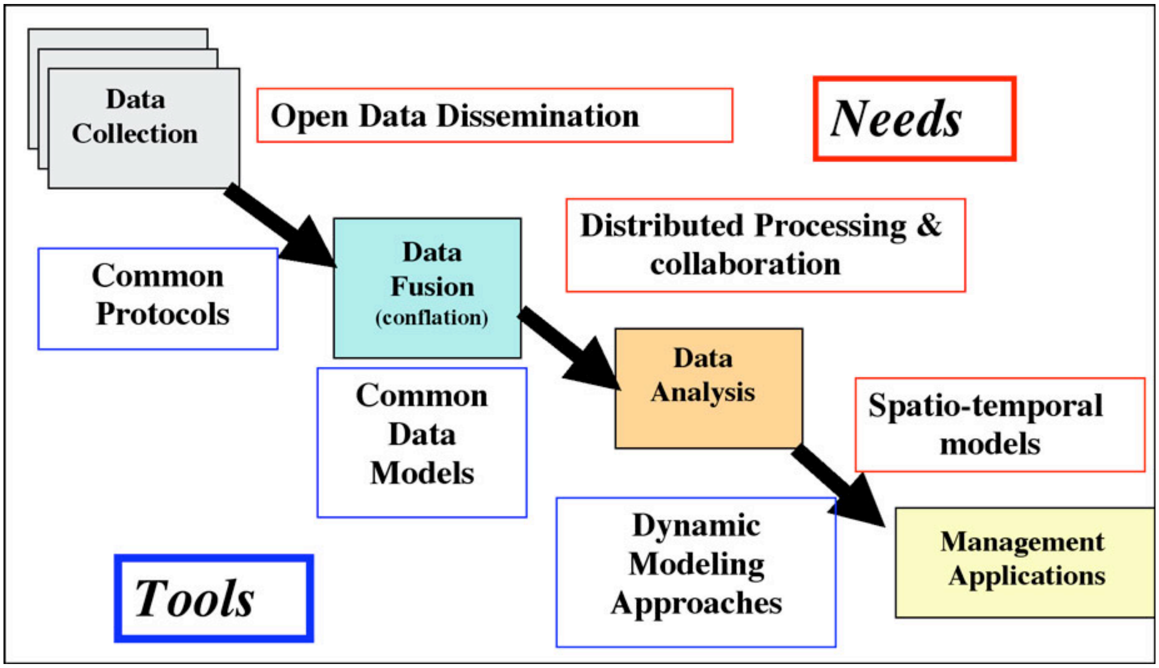

Figure 13.2. Marine spatial analysis needs and major areas of marine GIS tool development: common protocols, common data models and dynamic statistical and modeling approaches (from Halpin, 2004).

As can be observed in the general flow chart depicted in Figure 13.2, improvements in the geospatial analysis process will need to occur along the data collection, data fusion, data analysis and finally to management applications steps of the process. The three general areas of needs are: better data dissemination, better distributed processing and collaboration, and better spatio-temporal models. The specific areas for geospatial technology advancement to match these needs will come through the development of common protocols, common GIS data models and more dynamic modeling approaches. All of these needs and tool development processes are highly interconnected. The most profound advancements in the field of marine geospatial analysis will likely not be tied to any single area of technological development, but instead will be found at the ***intersection*** of these new spatial analysis, information systems, and modeling disciplines (Fig. 13.3).

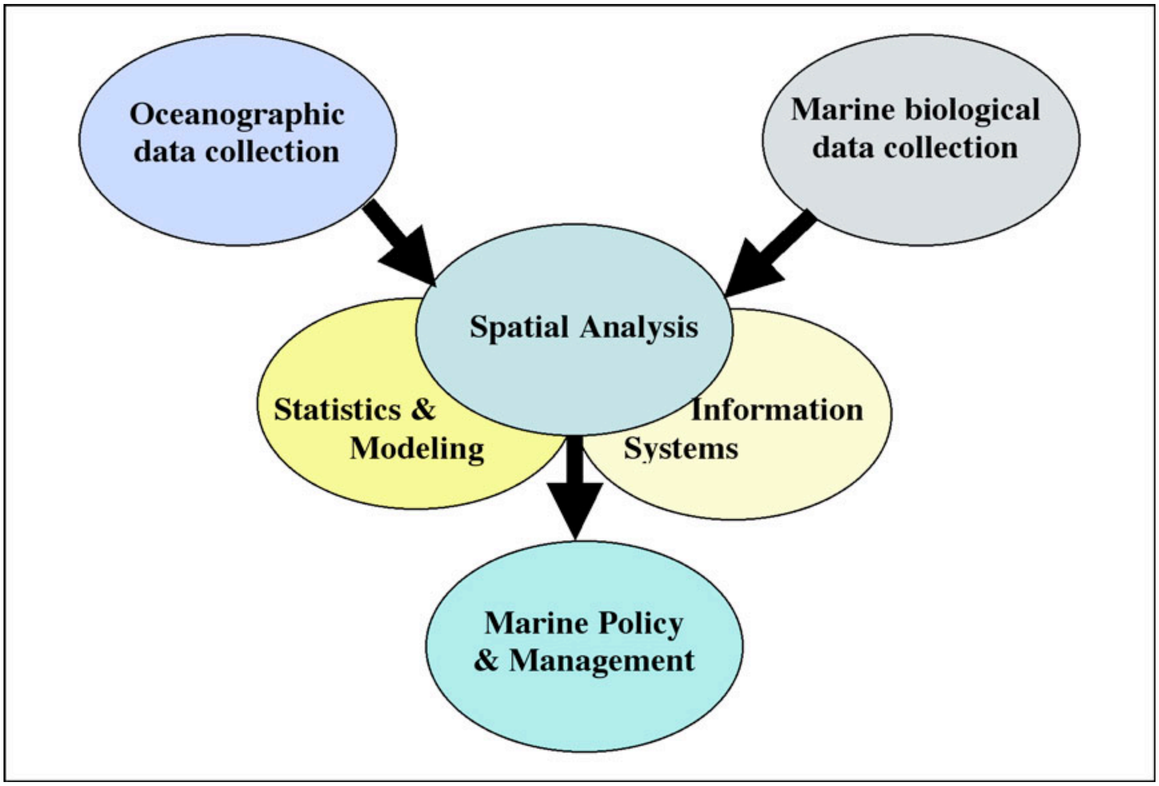

Figure 13.3. New advances in marine geospatial analysis will occur at the intersection of developments in spatial analysis, information systems and statistical modeling (from Halpin, 2004).

Grand Challenge: Data Access and Exchange

On one hand there is still a comparative lack of data for marine GIS as compared to its terrestrial counterpart. The land abounds with accurate and unmoving geodetic control networks, satellite sensors can see the land through the atmosphere but not through water at all depths, aerial photographs aid us in delineating landforms, land ownership, cities, and the like at much larger cartographic scales than in the ocean, as does the Global Positioning System on land. As has been stated many times, by various explorers and scientists with regard to the ocean floor, we have better maps of the moon, Venus, and even Mars, and we have sent more people to the moon than to the deepest parts of planet Earth (Challenger Deep in the Marianas Trench). Our mapping of the water column is extremely miniscule on a global scale, and the sensors that could provide detailed, three- and four-dimensional data about the dynamic marine environment generally do not exist, although enormous improvements in sensing technology have occurred in the past decade (Goodchild, 2000). Sampling or mapping may be rich in one-dimension (e.g., a vertical profile at a sampling station) but sparse horizontally, for which a great deal of interpolation must be relied upon in GIS (Wright and Goodchild, 1997; Schaefer and Schlueter, 2003).

On the other hand, there have indeed been tremendous advances in data collection techniques, that, as mentioned before, covering larger areas in two-dimensions add significantly to the information data streams now available to answer marine science questions. As such, we are faced with new challenges involving the synthesis, visualization and analysis of these disparate data types to maximize the utility of past, present and future marine data collection efforts. These challenges include critical needs for common data sharing protocols and technologies, common marine data types, development of specialized analysis tools for temporally dynamic applications, and new statistical modeling frameworks for better forecasting. To meet theses challenges, the marine science and management community will need to develop not only technological innovations, but also new priorities for the effective management and integration of marine science programs. The motivation for developing and accepting these new information systems approaches is found in the promise these approaches have for more accurately analyzing complex marine problems in a more objective and rigorous manner. The implementation of common data standards and protocols promises to allow for more efficient data sharing, higher quality analysis, and more direct linkage of spatial and temporal events in marine system.

There are three central areas of development that control our ability to effectively collaborate and exchange data: (1) data discovery and metadata standards; (2) data transport protocols; and (3) information system protocols. New developments in data discovery and metadata standards will provide the “card catalogue” for future marine scientists and managers to search Internet data warehouses and information system portal to discover and cross-reference data holdings. Because of the many spatial, temporal and trophic connections that may be inherent in any marine study, standards that control the way we locate relevant data are crucial. For example a research project involving geospatial analysis to support a management question may need to identify appropriate ocean bathymetry data, ocean temperature, wind speeds, sea heights, ocean color, prey species, predator species, management conditions, and fisheries data, all for a specific period in time and spatial resolution.

The emerging tools being developed involve setting standards, authoritative information sources and common protocols. An example is the Ocean Biogeographic Information System – Spatial Ecological Analysis of Megavertebrate Animal Populations (OBIS-SEAMAP) program (http://obis.env.duke.edu/). A request for the name of a marine animal species is first sent to the IT IS (Integrated Taxonomic Information System) taxonomic service to validate the taxonomic naming conventions and then passed on to searches for other spatial data records within the OBIS network. These types of interlocking searches are possible through the use of common XML (Extensible Markup Language) protocols and the establishment of authoritative sources on the Internet.

Once data are discovered, common data transport protocols must be developed in order to allow researchers to exchange data uniformly between sites. An example of common data transport protocols is the development of the OPeNDAP (Open-source Project for a Network Data Access Protocol) developed by a consortium of ocean data development programs (http://www.opendap.org/). The OPeNDAP program and similar efforts allow for the transport of data from site to site in common exchange formats, allowing researchers to standardize processing tool development and expectations. Examples of the OPeNDAP applications can be found at Live Access Server (LAS) data sites (example LAS: http://las.pfeg.noaa.gov); as well as the National Virtual Ocean Data System (NVODS). Figure 13.4 depicts examples of the data discovery and data transport protocols and standards that marine GIS data users will regularly encounter when searching, retrieving or publishing data over the Internet.

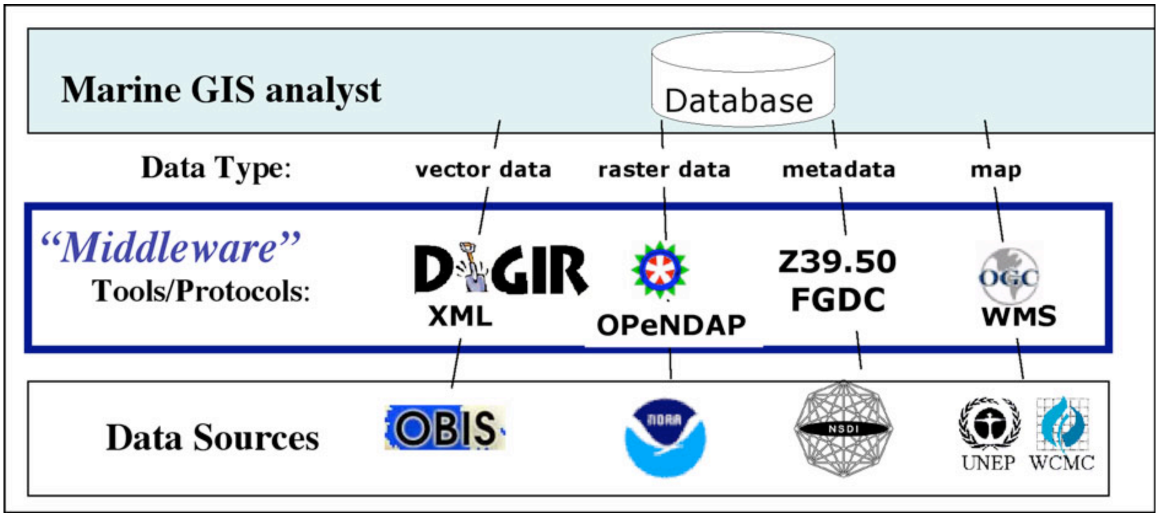

Figure 13.4. Common data discovery, data transport and Internet mapping tools, protocols and standards common to marine GIS operations (from Halpin, 2004).

In addition to protocols specific to geospatial data and processes, the marine GIS community needs to be evolving their operations in compliance with new standards and protocols that affect the entire Internet computing environment. The trend towards Internet based, collaborative projects in the field of marine GIS also means that the roles of individual researchers and practitioners are changing. There are new categories of "data providers", "data aggregators" and "data users" emerging to define the role and specialization of different individuals and institutions in large marine GIS projects. The Gulf of Maine Biogeographic Information System GMBIS project provides explicit examples of these emerging roles (http://www.usm.maine.edu/gulfofmaine-census/Docs/Research/Gmbis2.htm). These emerging specializations define a departure from the role of the single researcher taking a project from data collection, geoprocessing, spatial analysis and cartographic production of final results, and highlight the move to a broader information systems approach in the field.

In addition to the need for common data protocols, there are different user communities that need to collaborate more closely in the future. The operational oceanography and the biogeographic informatics communities are making advances in large information systems programs but tend to use mathematical scripting languages (e.g., MATLAB, IDL or Interactive Data Language, GMT or Generic Mapping Tools) to process spatial and temporal data. The “end user” marine management and conservation communities tend to use desktop commercial GIS packages. In order to bridge the gaps between these communities, efforts need to be made to develop more appropriate and interoperable software and data models for marine applications (e.g., Wright et al., 1998; Goldsmith, 2000).

As these varying communities interact, there will be a continuing need to formalize concepts and terms (i.e., ontologies) that will be used to aid the user in more effective searching and analysis of data and information (e.g., McGuinness, 2002) . For example, in the search for data and resources, one may use interoperable terms such as coastline vs. shoreline, seafloor vs. seabed, ecological resilience vs. robustness, scale vs. resolution, wetland buffering vs. GIS buffering, etc. Here the development of ontology repositories for marine data will be important, along with “semantic integration and interoperability” (e.g., Goodchild et al., 1999; Egenhofer, 2002; Kuhn, 2003), to aid in fully describing the context in which data were collected for its proper use, or for appropriate legacy uses beyond the initial mission or target of the data collection (allowing the user to understand the finger details of data collection and purpose without being a science or policy expert in that particular field). Emerging also is the concept of grid computing, where not only the data are distributed but the computing power as well (e.g., data may be executed on one machine for a numerical model, sent on to another machine for GIS analysis, rendered in 3-D and 4-D on another, etc.). A very successful example is GEONGrid, a geosciences-oriented network of federated servers (“a cyberinfrastructure” of sorts for geology and geophysics), based on a common set of services for data integration, exchange, modeling and semantic interoperability (Allison et al., 2003; Baru, 2004; http://www.geongrid.org).

Grand Challenge: Representation of Marine Data and Common Data Models

One of the most powerful features of a GIS is the ability to combine data of various types simply by assigning coordinates and displaying these “layers” together. Of course, this representation runs into difficulty if the data are dynamic, with constant changes in location or attribute, and best viewed that way, when the data represent entities of different scales, or when its dimensionality is three, four, or greater. Marine applications, with tides, upwellings, ships and vehicles moved by waves and currents, shorelines, and the like demonstrate all of these difficulties.

Shorelines are largely represented in GIS as fixed features but the daily reality of tidal fluctuations leads to the question of a shoreline according to whom? States vary in their definition of the shoreline according to tidal datum, some using Mean

High Water (MHW), while others use Mean Higher High Water (MHHW), or Mean Low Water (MLW). The depiction of a shoreline is fraught with uncertainty (where is the boundary for a rocky shore versus sandy shore versus tidal wetland?). There are significant differences between legal definitions and digital boundaries, as exemplified by a marine sanctuary boundary, where outer boundaries are explicitly described with coordinates, but inner boundaries follow a tidal datum such as mean high tide (Treml et al., 2002). When only half of the boundary is specified is spatially explicit, then one is forced to make assumptions concerning scale, accuracy, and precision. And then there is the inimitable question: “How long is a shoreline?” (Mandelbrot, 1967).

Much has been written about the importance of error and uncertainty in geographic analysis (e.g., from Chrisman, 1982 to Heuvelink, 1998), and with the challenge of gathering data in the dynamic marine environment from platforms that are constantly in motion in all directions (roll, pitch, yaw, heave), or in tracking fish, mammals, and birds at sea, the issue of uncertainty in position is certainly critical. We must accept that no representation in two-, three-, or four dimensions can be complete. And there are further uncertainties in what the data indicate about the marine environment, or what the user believes the data indicate about the environment.

As noted by Bartlett (2000), one of the most important lessons to be learned from collective experience in marine GIS is the importance of rigorous data modeling before attempting to implement a GIS database. Indeed, data models lie at the very heart of GIS, as they determine the ways in which real-world phenomena may best be represented in digital form. A data model for marine applications must undoubtedly be complex as modern marine data sets are generated by an extremely varied array of instruments and platforms, all with differing formats, resolutions, and sets of attributes. Not only do a wide variety of data sources need to be dealt with, but a myriad of data "structures" as well (e.g., tables of chemical concentration versus raster images of sea surface temperature versus gridded bathymetry versus four-dimensional data, etc.). It has become increasingly obvious that more comprehensive data models are needed to support a much wider range of marine objects and their dynamic behaviors.

As an example, Figure 13.5 shows a summary of common marine data types that is part of the conceptual framework of the ArcGIS Marine Data Model, a software industry data model involving a collaboration of ESRI with Oregon State University, Duke University, the Danish Hydraulic Institute, and NOAA Coastal Services Center (http://dusk.geo.orst.edu/djl/arcgis; http://support.esri.com/datamodels). The common marine data types extend current GIS data structures (points, lines, polygons, and rasters) to include more temporally referenced data structures that will allow for better representation of spatially and temporally dynamic marine data. For example, an "instantaneous point" would provide for marine observations that are tied to a single moment in time, while a "time-duration line" feature would represent a ship track or other feature that moves along path in space and time. The "common marine data types" are intentionally generic, to provide the most basic spatial and temporal features and relationships needed to develop marine GIS application. Users involved in specific application areas would need to select and refine the core features they need to develop more detailed applications.

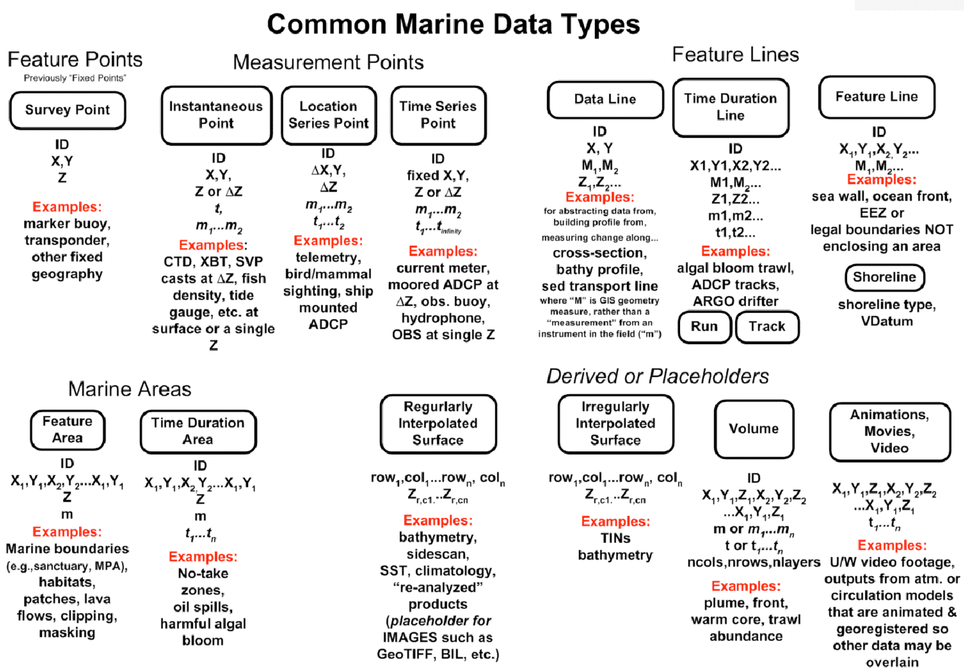

Figure 13.5. In order to develop more appropriate data structures to represent and relate coastal and marine GIS features, a draft set of common marine data types was developed as part of a fundamental conceptual framework for the ArcGIS Marine Data Model.

This ongoing project seeks to promote the interoperability of data and software for scientific and resource management users by providing the international marine GIS user community with a generic template to facilitate easier and faster input and conversion of data, better map creation, and most importantly, the means for conducting more complex spatial analyses by capturing the behavior of real-world objects in a geo-database.

Figure 13.5 focuses on the initial acquisition of marine data, and is thus concerned with the accurate sensing and collection of measurements from the marine environment, the dimensionality of these measurements, and their transformation from raw to processed for GIS implementation. Although it covers many of the data types used in all disciplines of oceanography and marine resource management, note that the 2-D, 3-D, and 4-D types are still classed as “placeholders” for the model (i.e., the GIS software is still unable to handle these data types satisfactorily and they are not available for many parts of the world ocean). As pointed out by Albrecht (2003), the development of application-specific conceptual models of objects and events, that include not only behaviors but also behaviors that can adapt to changing contexts, poses a major intellectual challenge.

In the end, how does one most effectively summarize, model, and visualize the differences between a digital representation and the real world? As the Earth's surface (water or land) is infinitely complex, decisions must be made about how to capture it, how to represent it in a digital system, how and where to sample it, and about what data format options to use in the GIS. This includes dealing with the inherent fuzziness of boundaries in the ocean, and addressing the multiple dimensionality and dynamism of oceanographic data, handling the temporal and dynamic properties of the seafloor, the water column, the sea surface, and the shoreline.

Grand Challenge: Dynamic Modeling in Space and Time

Probably the most interesting of the grand challenges facing marine GIS is the development of more dynamic models representing marine processes in space and time. The dynamic processes we are interested may be geophysical, ecological, resource management or economic in nature, but all of them will require fundamental adaptations to the way we collect, process, analyze and validate our data and our assumptions. It is still very difficult to imbed dynamic oceanographic models seamlessly into a GIS environment.

The questions that managers and policy makers are asking are becoming increasingly specific. More than ever now geospatial analysts are being asked to provide information to help forecast change over time. Parallel to the constraints we find representing a four dimensional ocean environment with two dimensional maps, our ability to forecast complex relationships at short time-intervals is constrained by statistical modeling approaches that were often originally developed for more static analyses. New developments in time-series and spatio-temporal modeling approaches are going to be crucial to completing the analytical framework of marine geospatial analysis. Many of these may be borrowed and adapted from the geocomputation, including diffusion modeling, time series regression, cellular automata and network, extensions, differential equation modeling, and spatial evolutionary algorithms (e.g., Box, 2000; Yuan, 2000; Peuquet, 2002; Albrecht, 2003; Green and King, 2003b)

Conclusion

This chapter has reviewed the fundamental role of geospatial thinking and analysis to coastal and marine science and management, the current state of marine GIS and geospatial analysis, and some insights on longstanding challenges and future trends in data access and exchange, representation and modeling of marine data, and dynamic spatio-temporal modeling of processes (physical, ecological, and socio-economic). The demands on the marine GIS community for increased precision, accuracy and more detailed analytical models have been increasing rapidly over the last several years and will continue to increase in the future. This in turn is forcing a rapidly increasing need for significantly more robust:

- data dissemination tools;
- spatio-temporal data standards & protocols;
- distributed processing & collaboration tools; and
- dynamic modeling & analysis tools.

As these demands for “precision management” and robust tools increase, it will be appropriate and timely to re-examine underlying data models in GIS and to develop new approaches particularly with regard to large-scale regional, interdisciplinary academic research projects. Such projects, within the new paradigm of “distributed” collaboration, will have an impact on both marine and terrestrial GIS. And marine GIS will continue to pose fundamental questions in the representation and analysis of spatial and temporal information, chief of which may be “how does one represent combinations of geometric objects and scalar fields, especially when the data are ‘in flux’?” In order to take full advantage of new innovations in marine spatial analysis, end users will need to keep up with emerging trends from the information systems, spatial analysis and statistical analysis communities.

Future advances will take time. The archival nature of terrestrial GIS has meant that large GISs have been reticent to adopt new algorithms, much less new data models, as many users have needed a stable platform for their work. However, advocates of software component technology (e.g., Microsoft’s Component Object Model, Sun’s Java Beans, etc.) convincingly argue that the GIS of the future will not be monolithic, but will be composed of intercommunicating modules, once interfaces for geospatial information can be standardized and published. The Open GIS Consortium (http://www.opengis.org) and others are pushing strongly in this direction. These efforts imply that prototypes that validate alternative representations or computational approaches, such as those posed by marine GIS, are especially valuable now, while standards are being considered and established. The increasing visibility of marine GIS and marine geospatial analysis as an essential tool for marine science and management is a testament to its growing usefulness across the field.

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