A New Global Coastal Database for Impact and Vulnerability Analysis to Sea-Level Rise

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ABSTRACT


A new global coastal database has been developed within the context of the DINAS-COAST project. The database covers the world's coasts, excluding Antarctica, and includes information on more than 80 physical, ecological, and socioeconomic parameters of the coastal zone. The database provides the base data for the Dynamic Interactive Vulnerability Assessment modelling tool that the DINAS-COAST project has produced. In order to comply with the requirements of the modelling tool, it is based on a data model in which all information is referenced to more than 12,000 linear coastal segments of variable length. For efficiency of data storage, six other geographic features (administrative units, countries, rivers, tidal basins or estuaries, world heritage sites, and climate grid cells) are used to reference some data, but all are linked to the linear segment structure. This fundamental linear data structure is unique for a global database and represents an efficient solution to the problem of representing and storing coastal data. The database has been specifically designed to support impact and vulnerability analysis to sea-level rise at a range of scales up to global. Due to the structure, consistency, user-friendliness, and wealth of information in the database, it has potential wider application to analysis and modelling of the world's coasts, especially at regional to global scales.

ADDITIONAL INDEX WORDS: Segmentation, coastal geographic information system (GIS), data model, climate change, global change.

INTRODUCTION

The expected accelerated rise in global mean sea levels through the 21st century may cause a number of physical changes to the world's coasts and hence can endanger coastal populations and infrastructure, as well as threaten many coastal ecosystems (McLEAN et al., 2001). The sensitivity of the coastal zone to sea-level rise, in conjunction with its importance in terms of social, economic, and ecological value (e.g., AGARDY et al., 2005; COSTANZA et al., 1997; TURNER, SUBAK, and ADGER, 1996), highlights the need for consistent national- to global-scale assessments of potential impacts and
possible responses to this global phenomenon and hence vulnerability to these changes. Such evaluations are an important component in the formulation of international climate change policies (Nicholls, Tol, and Hall, 2007), which are necessary for reducing the magnitude of potential impacts via mitigation (reducing greenhouse gas emissions) and/or adaptation to sea-level rise and climate change.

Global and regional vulnerability studies have provided quantitative assessments of potential impacts of sea-level rise at global and regional scales (e.g., Gornitz et al., 1994; Hoozemans, Marchand, and Pennekamp, 1993; Mimura, 2000; Theiler and Hammar-Klose, 1999). However, the scope of these studies has been limited by the available data in terms of resolution, coverage, parameter availability, and dated sources: this is a generic problem for broad-scale coastal analysis (National Research Council Staff, 2004). In addition to these limitations, data quality and integration constitute further problems; even in those cases where data and tools are available to coastal scientists for the analysis and modelling of coastal processes, these usually exist in fragmented forms. This fact compromises the consistency, reliability, and versatility of evaluations based on such sources. It has long been recognised that appropriate and reliable information within organised, planned, and coherent coastal databases is an essential prerequisite for coastal zone management (Weyl, 1982), and such systems continue to be developed (e.g., Bartlett, 2000; Bartlett et al., 1997; Millard and Brady, 2000; Vafeidis et al., 2004). The importance of data quality and integration is also reflected in the proposal of the U.S. National Research Council for a geospatial framework for the U.S. coastal zone (National Research Council Staff, 2004).

In order to address the preceding issues and provide a consistent source of data at global scales, the Dynamic and Interactive Assessment of National, Regional and Global Vulnerability of Coastal Zones to Climate Change and Sea-Level Rise (DINAS-COAST) project has developed a new global coastal database termed the Dynamic Interactive Vulnerability Assessment (DIVA) Coastal Database (DINAS-COAST Consortium Staff, 2006a), which is available at http://www.civil.soton.ac.uk/DIVA and http://www.dinas-coast.net. This database contains physical, ecological, and socioeconomic parameters and covers the world's coast, excluding Antarctica. It underpins the DIVA modelling tool that the project has developed (DINAS-COAST Consortium Staff, 2006b; Hinkel and Klein, 2007; Nicholls, Klein, and Tol, 2007). This modelling tool enables users to analyse a wide range of mitigation and adaptation policies in terms of coastal impacts and vulnerability by producing quantitative data on a range of coastal and socioeconomic scenarios at national, regional, and global scales, including adaptation (and mitigation) strategies. For this reason, the database has been specifically designed to address the data requirements of the project and the needs of researchers in the area of vulnerability assessment of coastal zones. It is also expected to be used for wider assessment of regional and global coastal issues.

This paper discusses the importance and the role of global databases in assessing global and regional coastal vulnerability to sea-level rise, emphasises the need for a new global coastal database, and presents the database that has been developed within the DINAS-COAST project. Within this context, existing data collections and databases that have been specifically designed for the coastal zone are reviewed and the new characteristics and comparative advantages of the DIVA Coastal Database are assessed. Furthermore, an overview of the database is presented and its potential use in coastal analysis is discussed.

**GLOBAL COASTAL DATABASES: AN OVERVIEW**

In the last two decades, the availability of digital spatial data for the world's biomes has vastly increased as a result of advancements in data capture and input techniques (Peuquet, 1998). Nevertheless, collections of data are not necessarily adequate for the needs of global-scale analysis, as merging data from various sources may raise several questions (Flewelling and Egenhofer, 1999). As Tomlinson (1988) observes, the way in which Earth observations are stored and integrated largely determines the degree to which spatial processes can be understood. Therefore, well-organised and designed data systems are needed to underpin our understanding of the processes taking place over large parts of the globe, including the coast (Bartlett, 2000; Tomlinson, 1988).

The large increase in global data availability has had a significant impact on coastal science. New and better-quality data for large parts of the world's coastal areas on factors such as waves, water quality, sediment fluxes, and elevation are becoming available via remote sensing. These data are extensively utilised to support local-scale studies (Bryan et al., 2001; Scott Lee and Shan, 2003). At the same time, new spatial global datasets on various biophysical and socioeconomic parameters such as population distribution (CIESIN and CIAT Staffs, 2004; Landscan Staff, 2003) and recently gross domestic product density (Nordhaus, 2006) are being developed and upgraded in order to satisfy data needs for interdisciplinary analysis. However, the forms in which these vast volumes of data exist and the difficulties involved in the process of integrating them are still a major barrier to their systematic utilisation within impact and vulnerability analysis. Commonly encountered limitations include (1) different data formats, (2) incompatible projections between datasets, (3) high costs for integrating nondigital datasets, (4) lack of metadata, and (5) incomplete spatial coverage. Providing linkages among different data types, datasets, and databases, in order to enable their combined use, and making this information available to nonspecialised users and policy makers can greatly enhance the potential of existing data and tools in assisting the coastal science community (Vafeidis et al., 2004). Some attempts have been made, especially in recent years, to develop global databases for the world's coastal regions. While these databases are an improvement on existing available datasets, they remain limited in various aspects, such as the type and amount of information they contain or the choice of the data model for the representation of information. These existing coastal databases are assessed here.
Examples of Coastal Databases

Due to the complex and dynamic nature of coastal zone systems, their analysis implies the need to simultaneously model multiple processes and their interactions rather than single isolated processes. For such analysis to be viable, the underlying data needs to be harmonised and held in a single, well-structured database (Roberts and Moore, 1998). Examples of limited sets of global- or regional-scale coastal data include the Sea Around Us Project (SAUP) database (http://www.saup.fisheries.ubc.ca) (Alder, 2003); CoastBase, the European virtual coastal and marine data warehouse (http://www.coastbase.org); the EUROSION database (http://www.eurosion.org); and the Land–Ocean Interactions in the Coastal Zone (LOICZ) typology (Maxwell and Buddemeier, 2002). The main characteristics of these databases are summarised in Table 1.

These databases include collections of existing datasets, as well as additional data generated for the purposes of projects in which the databases were developed (e.g., EUROSION). The coastal element of the SAUP database is a subset of the global ocean database and includes a series of biophysical parameters and some additional attributes, such as the percentage of water area covered by wetlands (Chuenpagdee and Pauly, 2004). The EUROSION database is fully integrated within a geographic information system (GIS) and was built to support the assessment of coastal erosion in Europe. It includes a series of parameters that impact coastal erosion processes and data on protection measures (e.g., coastal defences). The LOICZ database is probably the most comprehensive collection of coastal parameters at global scale, prior to the DIVA database, as it merges numerous global datasets and contains a wealth of information on physical parameters. It was developed to provide a basis for categorising coastal and marine environments at global and regional scales, including upscaling detailed studies (e.g., Buddemeier et al., 2002, pp. 48–51; Crossland et al., 2005), and underlies LOICZview, an online interactive software tool for statistically classifying such data and for assisting environmental scientists in developing coastal typologies. Finally, CoastBase aimed to link existing databases and new aggregated data in an attempt to design a European virtual coastal and marine data warehouse to improve coastal and marine information search and exchange. However, it did not reach the point of developing the actual data warehouse and remains a prototype that contains a very limited set of data sources (Eleveld, Schrimpf, and Siegert, 2003).

The EUROSION, LOICZ, and SAUP databases probably constitute the most comprehensive attempts to effectively merge coastal data at regional to global scales. Nevertheless, they are limited by factors including the type of the data model, the forms in which the data can be distributed, and the limited socioeconomic coverage, which in most cases consists of population data. Some of these limitations stem from the fact that the previously mentioned databases, with the exception of EUROSION, were not originally designed or did not include data intended solely for coastal applications; not all are focused on the coastal zone but also cover inland or ocean regions. The data model has been determined primarily by the form in which the underlying data exist, which in most cases is a raster data model (with the exception of the EUROSION database, which combines different data types). Despite its advantages in most global applications, the raster data format can be inefficient for coasts due to their essentially linear nature; raster also gives a fixed database resolution, which does not always address the requirements of coastal analysis. Finally, the available datasets are in formats that require the use of GIS software and expertise. These factors can significantly limit the potential use of these databases in coastal modelling and analyses, including impact and vulnerability analysis.

THE DIVA COASTAL DATABASE

Recognising the need for a new global-scale data system to produce reliable evaluations of coastal impacts and adaptation, the DINAS-COAST project set as one of its primary objectives the compilation of a new global coastal database. This database has been designed specifically for impact and vulnerability analysis under sea-level rise. It is intended to form a consistent basis for producing reliable evaluations of coastal vulnerability. The database is one of the three principal elements of the DIVA modelling tool, which also includes a range of interacting impact/adaptation algorithms and a graphical user interface (Hinkel, 2005; Hinkel and Klein, 2007).

Due to its explicit spatial nature, the database was initially developed within a GIS. A new data model was developed to represent coastal space, which decomposed the world’s coast into a series of linear segments. It is noteworthy that most impact and vulnerability analyses have explicitly or implicitly employed some form of coastal segmentation to create a data structure. Such an example is the first Global Vulnerability Assessment, where the database structure was essentially based on national boundaries, producing 192 segments (Hoozemans, Marchand, and Pennekamp, 1993; Nicholas and Hoozemans, 2005). Segmentation of the coast into discrete coastal units is also applied at more detailed scales for the purposes of shoreline or coastal management (e.g., Brenner, Jimenez, and Sardia, 2006; Mangor, 2001).

In the following sections, the process of compiling the database is discussed. First, the data model and the structure that underlie the DIVA database are presented and their implementa-
tation is described. Then, the data sources and methods used for populating the database are examined. Finally, the important tasks of validation of the database and the generation of supporting metadata on the database are discussed.

**Representation of Coastal Space: The Data Model**

The decision regarding how to represent information in a system is an important factor for the organisation and reliability of a database. The data model and structure employed for describing the system have been identified by Bartlett et al. (1997) as two of the major concerns to the developers of coastal information systems. The most immediate of which is the selection of an appropriate model of coastal space. The representation of the coastline also affects GISs, which are founded on the assumption that the two horizontal dimensions are essentially equivalent (Goodchild, 2000). The common recognition of the coastline as a linear entity led Shupeng (1988) to suggest using a linear model for coastal databases, a suggestion that many researchers have followed (e.g., Fricker and Forbes, 1988; Sherin, 2000; Sherin and Edwardson, 1996).

Based on the concept of linear representation of the coastline, the DINAS-COAST project created a global model of coastal space in which geographic information is represented as a collection of geographic features (Hinkel, 2005; Hinkel and Klein, 2007). All data are expressed as attributes of seven geographic feature types, namely, linear coastline segments of variable length, subnational administrative units, countries, major selected rivers, major selected tidal basins or estuaries, world heritage sites, and relevant climate and sea-level scenarios based on the grid of the Climate and Biosphere Groupe (CLIMBER) climate model as described by Ganopolski and Rahmstorf (2001). The fundamental core of the database consists of the linear segments, and all attribute data are spatially referenced to the relevant coastal segments, which possess unique identifiers that link the different feature types via the coastal segments (Figure 1). The segmentation model is designed to define homogeneous units for vulnerability analysis at the (broad) scales of analysis. These units are defined based on the longshore variation of several parameters related to (1) coastal geomorphology (related to the natural system response), (2) population density (related to human exposure/response and the human dimension), and (3) administrative boundaries (related to political decision-making entities) (McFadden et al., 2007). While these variables are not comprehensive, they represent a selective set of boundary conditions across the natural-human system divide that allow objective segments to be defined at an appropriate scale for the DINAS-COAST project. The spatial variability of the broad-scale parameters becomes the reference unit for the segmentation: the point at which a parameter changes along the coast is plotted against the coastline, defining a linear stretch or coastal segment. Each segment reflects a changing response or sequence of responses within the coastal system to sea-level forcing. All attribute data are then referenced to these autonomous units, using methods and metrics discussed in the following sections. An analytical description of the segmentation rules, the underlying data, and the rationale underpinning the methodology can be found in McFadden et al. (2007).

According to this methodological framework, the segmentation of the coastline was implemented within a GIS. The Digital Chart of the World (DCW) coastline (Environmental Systems Research Institute Staff, 2002) was employed as the base layer since its size, scale, and level of detail were the most optimal available, in terms of information content and computational requirements, for a global database. However, for the purposes of the present study, around 1500 small islands and atolls, which are areas known to be particularly vulnerable to sea-level rise (Nurse et al., 2001), were added to the original layer. These additional islands and atolls, not included in the DCW, were selected from the more detailed World Vector Shoreline dataset (SOLURI and Woodson, 1990). Based on the preceding coastline and using global datasets (Table 2) containing spatial information on the distribution of the segmentation parameters that were described earlier in this section, the segmentation was implemented in a series of steps. Each step involved splitting the coastline at the points where the values of each of the parameters changed, thus generating segments with uniform values along their length. This process was performed using standard GIS operations and techniques such as dataset projections, format conversions, overlay analyses, and buffering (Longley et al., 2001). The segmentation process divided the world's coast into 12,148 segments (Figure 2), which constitute the fundamental spatial reference units for the database, the integrated modules, and the graphical user interface of the DIVA modelling tool.

**Populating the Database**

Compilation of the database was based on a series of primary and secondary data sources (Table 2). Primary data included datasets derived from remote sensing that offer a glob-
The integration of primary and secondary data sources offers the most promising approach to compiling up-to-date and scientifically valid global databases (Rhind and Clark, 1988). It should be noted that integration of multisource data is prone to numerous limitations (e.g., variable temporal and spatial scaling, different formats, and different levels of reliability) but nonetheless essential (Tomlinson, 1988).

The integration of coastal datasets from such a large variety of data sources constituted a significant challenge as the spatial data "inheritance" unavoidably produced variations in quality, timeliness, and coverage. All digital datasets acquired, and all analogue ones converted to digital form, were processed and customised to a standard form in order to overcome inherent variations in geographic extent, map projections, and data representation. One of the most important aspects of this work was the geographic integration of the datasets collected or generated. Georeferencing can constitute a major problem even in large-scale (i.e., small-area) studies (Mueller, Meissner, and Weinrhein, 2002). For this purpose, a series of global projections were used for performing projection-dependent calculations. These projections were selected depending on the processing needs and the nature of the individual datasets. After preprocessing was completed, all data were referenced to the common Geographic Reference System WGS1984 Datum.

Using the storage and analytical powers of a GIS, all database parameters were referenced to the coastline segments (Figure 3) and were exported in the form required by DIVA (consistent with the seven geographic features). The process-
ing undertaken included GIS operations such as resampling, proximity analyses, buffering, and map algebra zonal functions (Longley et al., 2001), which were employed for calculating some function or statistic of the input data values located in zones defined by the coastline segments. These zonal functions were applied to all coastline segments for various tasks, such as for calculating spatial statistics (e.g., average population density along a segment) or for quantifying the geometric characteristics of the segments (e.g., coastline length). Although the coastline segment is a linear unit of reference, the values of the individual parameters also often include an implicit “depth,” as they have been calculated for a coastal zone that extends inland. The width of the zone varies depending on the nature of the parameter and the form of the original data. Therefore, parameters such as coastal slope were calculated directly on the linear representation of the coast (e.g., based on the values of pixels intersected by the vector line of the coast), while others, such as the area of mangroves, were calculated at variable widths following the extent of the borders of their polygon representation. Analytical descriptions for how the values of each parameter were calculated can be found in the DIVA metadata documentation (Vafeidis et al., 2006). The values resulting from these operations were then attributed to the respective coastline segments, thus compiling the DIVA database. The database in its final form includes information on more than 80 physical and socioeconomic parameters at the coast (e.g., Table 2).

Validation

The compilation of the database was followed by extensive testing which aimed to identify errors or omissions in the data, ensure that the data had been correctly transferred to the coastline segments, and examine the internal consistency of the database. To identify gaps in the global coverage or potential errors in the data, the analytical and processing capabilities of GIS were employed and the standard spatial analysis functions already mentioned in previous sections were used for exploring the data and comparing them against other datasets. The methodologies employed varied depending on the type of the dataset. Errors in the original data or gaps in coverage were identified and corrected utilising data from additional sources (e.g., local-scale datasets) or on the basis of the DINAS-COAST consortium’s expert knowledge when data were not readily available. It has to be noted that when external data sources (e.g., population and elevation datasets) were employed for populating the database, the validation process did not involve a detailed evaluation of the accuracy of the original datasets used as it was assumed that this process had been performed by the creators of the datasets. Instead, the validation process could be better described in those cases as a general assessment of the quality of the employed data and of their suitability in being transferred to the data model used in the DIVA database.

In the second and third steps of the validation process, a series of algorithms was generated for evaluating the transfer of data to the unit segments and the internal consistency of the database. The process, which was fully automated, did not detect errors but identified areas where improvements in the spatial referencing of the input data could be made. These areas contained 2.5% of the total number of segments (approximately 300 segments), and updates were implemented automatically based on the logging outputs of the algorithms. The updates primarily included corrections in the process of referencing attribute data to the geographic features using additional information from the results of the validation algorithms (e.g., an attribute value based on the proportional length of a coastal sediment situated within a zone of a specific value rather than based on the mean value of the zones intersected by the segment). The results of the validation process are described in detail in the associated DIVA metadata document (Vafeidis et al., 2006).

Metadata

Recognising the fundamental importance of effective metadata to describe all constituent datasets and, hence, to support widespread use of the database by user groups both within and outside the DINAS-COAST consortium, a detailed metadata information document was created (Vafeidis et al., 2006). This document contains information for all parameters of the DIVA database, including all geographic features of DIVA (coastline segments, administrative units, countries, tidal basins, rivers, world heritage sites, and CLIMBER grid cells). Information is listed according to the system properties of the DIVA model (parameters, initialised variables, and drivers) (cf. Hinkel and Klein, 2007). The metadata include detailed descriptions of the individual parameters and initialised variables, information on the data properties and on the underlying data sources, a presentation of the methodologies employed for generating datasets, and methods and techniques used for attributing the data to the coastline segments.

DISCUSSION AND CONCLUSIONS

A new global coastal database has been compiled within the DINAS-COAST project. This database was specifically designed to address the needs of vulnerability assessment of coastal zones under sea-level-rise scenarios. It merges data of different types and from various sources to create a consistent and coherent source of information based on physical and socioeconomic parameters within the coastal zone, and it covers the entire globe, excluding Antarctica. Rather than being a static collection of georeferenced digital data, the DINAS-COAST database provides a flexible data system relevant to current assessment and understanding of coastal vulnerability to sea-level rise. It is in a form amendable to subsequent analysis and progressive upgrade as new and more detailed datasets emerge or the data requirements of the DIVA model expand. Importantly, this new database has a fundamentally different structure from that of all other global datasets, which are primarily based on raster data models. The representation of the coast in DINAS-COAST is based on the concept of a linear model. This type of representation constitutes an improvement compared to earlier linear data models of the coast, as it does not divide the coast in an arbitrary way but is instead based on a series of scientific criteria (McFadden et al., 2007).

The structure and contents of the database reflect the priorities, aims, and perspectives of the DINAS-COAST project.
(cf. Bartlett et al., 1997), and in that sense they have been defined largely by project-specific needs. However, the methodological and structural advances achieved extend beyond the boundaries of the DINAS-COAST project. It is expected that the cross-disciplinary nature of the DIVA database will support other types of coastal analysis on global and regional scales, such as global change studies within the International Geosphere–Biosphere Programme and IHDP LOICZ project (Crossland et al., 2005; Kremer et al., 2004). The global coverage of the database ensures accessibility to broad-scale data in areas where detailed information is not readily available. The greatly improved global wetland component of the database, for example, has underpinned a new and improved broad-scale model of wetland vulnerability. The model provides a dynamic and integrated assessment of wetland loss and, drawing on parameters from the database, estimates transitions among different vegetated types and open water under a range of scenarios of sea-level rise and changes in accommodation space through human intervention (McFadden, Spencer, and Nicholls, 2007). In addition to its potential as a source of input data, the database can be employed as an independent source for the validation of model results. Finally, it must be noted that due to its global coverage, the information contained in the database is not appropriate for analysis at local scales and should be evaluated considering all limitations associated with global datasets. Particular attention must be given to the fact that the scope and scale of the DIVA database render it inappropriate for coastal management decisions due to data uncertainties associated with the database’s intended use in global and regional climate policy analyses. Nevertheless, the database can provide a valuable tool for highlighting areas where further in-depth analysis is necessary, thus assisting in the prioritisation of regions where coastal management at local scales is more urgently required.

Despite the previously mentioned restrictions, the interdisciplinary nature, the consistency, and the user-friendliness of the database render it a significant advance in the field of global coastal databases and can provide an effective basis for the modelling and analysis of coastal processes at regional and global scales. Future work may include updating the database with new data as these become available, upgrading of the database with larger-scale and higher-resolution data for specific regions, refining the coastline segmentation for regional to local case studies, and updating the database with local-scale data, thus rendering the database suitable for coastal management issues in those regions. This might require nested ed databases, as at finer scales a linear data model may be less appropriate: this is a topic for further research. Such work can form the basis for creating a database that links data across a wider range of scales and can therefore constitute an innovative tool for coastal analysis across different scales.

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