United Nations Institute for Training And Research

Explorations in Geographic Information Systems Technology

Volume 3

Applications in Coastal Zone Research and Management

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Introduction

This workbook is the third volume in the UNITAR *Explorations in Geographic Information Systems Technology* series. Like previous volumes it incorporates a review paper and a series of GIS exercises relevant to a particular application. In this case, the application is coastal zone research and management. It was thought that researchers and managers would benefit from a review of coastal studies that use GIS as well as a set of exercises designed to explore typical applications.

GIS technology is challenged by the coastal zone's dynamic character, its linear features, and its three dimensional (marine) aspect. It is pushed to model fluid processes and complex patterns of marine/terrestrial interaction. Although the coastal zone presents many difficulties for the effective use of GIS (see Darius Bartlett's paper in this volume), it is rapidly becoming a powerful tool for monitoring and modeling the unique processes of the coast. Coastal zone applications should continue to provide a vital stimulus to advances in GIS technology.

Likewise, coastal research is benefiting from the use of GIS tools. GIS is uniquely qualified to manage and analyze the ever increasing layers of coastal data becoming available. Traditional tasks such as charting coastal bathymetry and shoreline change are made easier. In addition, procedures of spatial analysis, only practical since the advent of GIS technology, are being applied in coastal zone research (e.g. change analysis and fluid dispersion modeling).

Our research has lead us to conclude that the potential for GIS to contribute to coastal zone studies is quite large. In addition, we have found that there is a substantial need for educational materials relating to this application. For these reasons we feel a coastal zone/GIS workbook is both timely and appropriate. Hopefully, this volume will provide a basis for the continued advance of GIS as a vital tool in coastal zone research and management.

Production of this workbook at the IDRISI[1] project was truly a collaborative effort. The review paper and much guidance were enthusiastically supplied by Darius Bartlett, University College, Cork, Ireland. Much of the data and methodology for the exercises was contributed by coastal zone researchers from around the world. Their generosity is greatly appreciated. And finally, the talents of the workbook production team here at the IDRISI project were combined in all phases of exercise design, writing, and testing. The team consists of

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Their cheerful and professional attitudes made producing this workbook a pleasure.

In addition, many thanks to Nassrine Azimi and Steve Gold of the UNITAR European Office for their valuable assistance throughout the production of this and other workbooks.

Kevin St. Martin, Worcester, 1993.

1. IDRISI is a raster-based Geographic Information System for microcomputers that has been developed and is distributed on a non-profit basis by the Clark Labs, Clark University, Worcester, MA 01610, USA. Development of the IDRISI system has been supported by Clark University, the United Nations Environment Program Global Resource Information Database and the United Nations Institute for Training and Research.

Exercises

The exercises in this workbook assume that users will have a basic understanding of GIS concepts and methods. In addition, exercise procedures have been written with respect to the IDRISI system only. However, an attempt has been made to sufficiently explain each step such that translations to other raster-based systems might be possible.

The exercises can be broken into four broad groups of processes relevant to coastal zone research and management. The first group (Exercises 1 and 2) concerns local and regional resource inventory and suitability analysis. While Exercise 1 examines shrimp fishing activities in South West Florida, its main purpose is to reacquaint users with basic GIS procedures and concepts. The second exercise of this group examines the detection of seagrass beds using remote sensing techniques, and also has an introductory tone.

The second group (Exercises 3 and 4) explore further remote sensing and methods of image processing for coastal analysis. Exercise 3 uses Landsat data for the North coast of the Dominican Republic to model bathymetry. An algorithm and a Principal Components Analysis method to find depth are used. Exercise 4 utilizes vector change analysis to examine the dame data set as Exercise 3 except in time series.

The next two exercises both model change in the coastal environment but from two different perspectives. Exercise 5 utilizes several years of depth profiles along a beach in Australia to model past sand erosion and deposition, while Exercise 56 models the future effects of seal level rise on landuse in Narragansett Bay, Rhode Island. In addition, Exercise 6 looks at the related issues of error analysis in predictive modeling.

Finally, the workbook concludes with two general GIS exercises. In Exercise 7, a number of data layers are brought together and an aquaculture suitability study is performed for the Gulf of Nicoya, Costa Rica. The last exercise uses a single digital terrain model to examine some considerations important to developing planning. In this case, viewshed analysis is used to find areas with panoramic views of the North Iberian coast.

Revision Notes

Notes to the Second Edition

This volume, originally printed in 1993, was revised and re-printed in November, 1995. The exercises and data were originally prepared for use with Version 4.1 of IDRISI. This revision incorporates changes to the text and data to facilitate its use with Version 1.0 of IDRISI for Windows. Some of the exercises were modified both to accommodate new software capabilities and to better explain the methods being illustrated. No other changes have been made to this volume.

Daniele Spirandelli, Revision Editor

Worcester, 1995

July 2002

This volume was revised in July 2002 to be compatible for use with the Idrisi32 Release 2 GIS and Image Processing software and for distribution in electronic format. The content of the volume is exactly the same as that of the previous version, except that specific instructions for the exercises are given for Idrisi32 Release 2 rather than older versions. In addition, minor editorial revisions have been made. The editor would like to thank David Benz, Chunling Liu and Nathan Moore for their valuable assistance.

Beth Suedmeyer, Revision Editor

July 2002

April 2005

This volume was revised in April 2005 to be compatible for use with the IDRISI Kilimanjaro GIS and Image Processing software and for distribution in electronic format. The content of the volume is exactly the same as that of the previous version, except that specific instructions for the exercises are given for IDRISI Kilimanjaro rather than older versions. In addition, minor editorial revisions have been made.

February 2007

This volume was revised in February 2007 to be compatible for use with the IDRISI Andes GIS and Image Processing software and for distribution in electronic format. The content of the volume is exactly the same as that of the previous version, except that specific instructions for the exercises are given for IDRISI Andes rather than older versions. In addition, minor editorial revisions have been made.

April 2009

This volume was revised in April 2009 to be compatible for use with the IDRISI Taiga GIS and Image Processing software and for distribution in electronic format. The content of the volume is exactly the same as that of the previous version, except that specific instructions for the exercises are given for IDRISI Taiga rather than older versions. In addition, minor editorial revisions have been made.

GIS and the Coastal Zone: An Overview

Darius Bartlett[1]

Introduction

Geographical Information Systems (GIS) are computer-based tools developed for handling spatially-referenced data and information. Normally, they integrate database administration functions with analytical tools and techniques for geographic analysis and computerized cartography. Although GIS is only some 30 years old, already the impacts of these new technologies are having major and far-reaching effects. Indeed, it has been claimed that GIS are "as significant to spatial analysis as the inventions of the microscope and telescope were to science" and that they represent "the biggest step forward in the handling of geographic information since the map" (Chorley, 1988, p. 8).

Given their importance in other areas of natural resource management, it might be anticipated that Geographical Information Systems would be natural tools for assisting planning and decision-making within the coastal environment. Indeed, the potential benefits that might be obtained from using GIS for coastal management was first recognized at least twenty years ago (Ellis, 1972), and this recognition has frequently been repeated since (e.g. Fricker and Forbes, 1988; Bartlett, 1989, 1990).

It is generally agreed that substantial savings in time, effort, and money could, in theory, be obtained by applying GIS to the coast. In practice the take-up and use of the technology for coastal management purposes has been remarkably slow (Bartlett, 1989, 1990). Nevertheless, while the application of GIS to problems of the coastal zone remains one of the major challenges of the GIS research agenda, a steadily growing body of literature testifies to an upsurge in interest in Coastal Zone Information Systems since the late 1980s (e.g. Davis and Davis, 1988; Law, 1991; Townend, 1991; see also Bartlett, 1993). The exercises presented in this workbook demonstrate that successful analysis of coastal zone problems may be obtained through judicious application of readily accessible GIS software.

The Coast and Human Society

The writer Margaret Drabble has suggested that "the coastlines of childhood imprint themselves forever on the memory" (in Greenpeace, 1987); and it is certainly true that for many people, particularly those who live on or near the shore, the relationship between people and the sea is one that transcends purely objective, rational description.

Even arriving at a formal and generally agreed definition of what constitutes the coast is remarkably difficult: in particular, while it is commonplace to refer to "the coastline", such a designation is misleading and implies an essentially linear configuration. In practice it is more correct and more useful in conceptual terms to refer to the "coastal zone." Carter defines (1988) the coastal zone as "that space in which terrestrial environments influence marine (or lacustrine) environments and vice versa," and this definition will be followed in this book.

However it is defined, the coastal zone as a region of the Earth's surface is of extreme significance for human affairs: many social, cultural, economic and political activities depend on, or are driven by, the characteristics of the coast. Today, some estimates suggest that up to 40% of the Earth's human population lives on or near the coast (Carter, 1988); while in the United States alone it is anticipated that soon approximately half the population will be living on coastal belts equating to some 5% of the total available land (Salm and Clark, 1984).

Given this growing coastal population, it is probably inevitable that human-induced pressures on the coastal system will occur. However, the relationship between society and the coast is a complex one, in which each has the power to affect the other. On the one hand, the influence of the coast upon human activities should not be underestimated: the shore shapes, molds, constrains and enables a whole range of human cultural and other endeavors. In particular, we are consum-

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ers of the coast in a number of ways, some more invasive than others:

* In many cases, the coastal zone provides the best, or the only, available land for urban development, agriculture, commerce, industry, transport, and other economic activities. Thus, the coastal zone provides the spatial milieu for much of society's functioning.

* Traditionally, the highways of the sea have provided important route-ways for trade, communication, invasion of new lands and, conversely, for defense against aggressors.

* The coast is also increasingly in demand as a location for leisure and recreational activities, ranging from formal holiday resorts, watersports centers and marinas to informal, often semi-wilderness areas, national parks, etc. As well as providing living space, the coastal zone also provides more tangible riches: coastal sediments often make extremely fertile soils for agriculture; while off-shore it is estimated that more than 99% of the world catch of marine fish species are now caught within 320 km of land. More than 50% of the total biological production of the ocean takes place in the coastal zone (Holt and Segenstam, 1982, quoted in Salm and Clark, 1984). We also obtain minerals and vital energy resources, particularly petroleum-based, from many of our coastal waters.

* Less directly, but equally important, is the moderating influence of the sea, which can ameliorate otherwise severe climates thus facilitating transport, agriculture and industry in the coastal hinterlands. The Atlantic coasts of northern Europe, for example, are kept effectively ice-free in winter by the warming effects of the Gulf Stream.

* Finally, and in apparent disregard for the value of the sea as a clean and untrammeled resource, we also use the off-shore zone as a convenient disposal ground for sewage and domestic and industrial wastes, including toxic and/or radioactive materials.

The coast does not only facilitate the workings of society: sometimes it can impede or restrict the range of available options. For example, by acting as a barrier to trade and communications, or by introducing a high level of vulnerability to natural catastrophe. Indeed, as Bartlett and Carter have pointed out (1991), "many of the most popular coastal regions are also the most dynamic, and frequently, the most hazardous locations to live in". Such considerations are particularly important for the populations of low-lying Developing World countries, such as Bangladesh, but are also of growing concern to the more affluent parts of the world such as the Atlantic margins of Europe (Carter, 1990; Devoy and Bartlett, 1991; Bartlett, et al., 1993), or the United States (Titus, 1984, 1987).

The spiraling growth of human population levels, and the parallel increases in technological capabilities since the industrial revolutions of the last two centuries, also mean that human activities may have their own important impacts on the coast. Such anthropogenic interference with coastal processes may be intentional (e.g. in order to mitigate flood or erosion hazard, or to create more exploitable land for agriculture) or unintentional (e.g. by the influx of agricultural fertilizers or other pollutants into the water of the near-shore zone).

These human-induced impacts often have important consequences for the well-being of the coastal system. Soucie (1973) puts this succinctly when he suggests that "the real conflict of the beach is not between sea and shore but between man and nature" (quoted by Komar, 1976, p2); while Bartlett and Carter claim that "the vitality of the coast is becoming increasingly at risk through human mismanagement, ignorance, indifference and neglect" (1991, p. 44). Anthropogenic influences may affect both the morphodynamic functioning and also the ecological processes of the coastal zone. They include:

* disruption of the physical coastal system, through the mining of sediments for construction purposes or agriculture and the dredging of sediments from rivers and harbors to maintain navigation (Carter, 1988);

* inappropriate use of coastal engineering structures, such as breakwaters, jetties, sea walls and coastal defenses, which may upset local coastal morphodynamics and introduce unforeseen problems of erosion and/or deposition within the coastal system (e.g. Carter, et al. 1983; Carter and Bartlett, 1990); and

* the destruction of habitats and genetic diversity through urban and industrial development, pollution, overfishing, introduction of exotic species and/or diseases, interference of natural processes within the coastal zone, and a host of other

activities (Salm and Clark, 1984).

Given the close interdependence between society and the coast, it is clear that the continued health of the marine environment and its coastline depends on the implementation of rational, integrated management strategies in preference to the somewhat piecemeal approaches of traditional coastal management (Carter, 1988; Bartlett and Carter, 1991). Unfortunately, while achievement of integrated coastal management policies is now an established and internationally recognized ideal, it must be stated that in practice coastal decision-making and planning is all-too-often conducted on the basis of inadequate conceptual, methodological or administrative structures, and may even be lacking in any clear goal (Shaw, 1982; Barisich, 1987; Eichenberg and Archer, 1987; Carter, 1988).

Applications of GIS in the Coastal Zone

While GIS have the potential to contribute to coastal management in a great variety of ways, a number of broad generic categories of application may be recognized.

Inventory

Many early applications of GIS to coastal matters focused on the ability of computer systems to store data, and to permit selective retrieval of records on the basis of *ad hoc* inquiries. Sometimes known as transaction-based processing, typical examples have included the RAMS inventory database (Eberhart, 1980; Eberhart and Dolan, 1980) which was developed to monitor developments along the shores of Chesapeake Bay and, more recently, the Northern Ireland sub-littoral survey (Erwin et al., 1986) which examined the distribution of marine benthic organisms.

In such applications, GIS can aid the sorting and rapid retrieval of data on the basis of location and other spatial relationships. Most proprietary systems nowadays, including IDRISI, provide the means for performing such links: IDRISI, for example, includes the DBIDRIS module, which enables data sets held in dBASE to be accessed for analysis and display.

Coastal Change Analysis

The use of GIS for time series and change analysis has been comprehensively discussed in an earlier volume in the present series (Eastman and McKendry, 1991), so the concepts need not be covered here. It is useful to note, however, that GIS are increasingly being used, often in tandem with remote sensing and image processing techniques, in order to monitor changes in coastal systems. In particular, wetlands have been extensively studied using such techniques (e.g. Christensen et al., 1986; Dahl, 1987; French, 1991), but the techniques have also been applied to analysis of erosion and shoreline changes (e.g. Mauriello, 1991; McBride, 1989; Demirpolat et al., 1989; Debusschere et al., 1992).

The dynamic nature of the coastal environment is one of its most important characteristics. The coast provides the setting for complex flows of matter, energy, organisms and information. These flows move in all directions and at a variety of spatial and temporal scales. The primary driving forces that power these exchanges are the short term weather and long term climate (Smith and Piggott, 1987), secular changes in sea level (Devoy, 1987), and gravity-driven tides (Beer, 1983).

Coastal erosion, flooding, silt deposition in harbors, and oil spillages are but some examples of how human affairs are intimately related to the dynamics of the coast. The processes encountered, and thus requiring analysis, can operate according to time scales ranging from less than a second to those measured in millennia or more (Carter, 1988; Komar, 1976). They may be progressive, cyclic (i.e. they ultimately return to the same starting point), chaotic, ordered, or completely random, and they may operate semi-independently of other phenomena or else may be intimately associated with, and dependent on, other components of the coastal system (e.g. Shaw, 1985; Carter, 1988; Bartlett and Carter, 1991). In spatial terms as well, these dynamic processes can operate over a wide range of scales, from those measured in millimeters or less to ones extending over tens or even hundreds of kilometers.

Partly because of this high degree of mobility the coastal zone provides the setting for many important natural environmental processes (e.g. erosion and deposition). Many important transfers of energy also take place at the shore, particularly in the transmission of heat from the oceans via the atmosphere to the land. Equally important, many marine organisms, and whole ecosystems, depend on the characteristics of the coast for their survival. The waters of the coastal zone, especially in estuarine and in-shore areas, are some of the most biologically productive areas of the earth, and underpin many aquatic and terrestrial trophic chains. Thus, for these and other reasons, the coastal scientist or manager increasingly requires access to technologies that can take account of the dynamics of the coastal system. Simulation of coastal processes by computer opens up important possibilities for clearer understanding of the shore, and of the likely impacts of management decisions.

The development and testing of dynamic process models and simulations of different abstractions of reality is one of the cornerstones of modern GIS. As well as allowing the impact of proposed developments to be assessed without risk of damage to the real-world coastal system computer simulation also offers other benefits. In particular, development of a successful computer simulation depends on the creation of a robust data model for representing the system variables within GIS (see below), and this in turn requires a meaningful conceptualization of the phenomena under study. Thus, the process of setting up the simulation can, itself, promote greater awareness of the constituent elements and relationships at work within the coastal system.

Once the data model has been created, subsets of variables and processes may be isolated for particular attention. Thus the analyst may simplify the complexity of the system and selectively isolate key parameters of concern for more detailed examination. Additionally, simulation modeling also allows compression of temporal and spatial scales to more manageable dimensions and, where appropriate, allows a time-series to be run "backwards," so that the starting point of some dynamic process may be derived from the observed end results.

Traditional simulation modeling of coastal phenomena has tended to focus on specific, discrete aspects of the coastal system such as sediment transport (e.g. Komar, 1983), contaminant plume behavior (e.g. Weyl, 1986), or wave mechanics (e.g. Beer, 1983). However, within a GIS context, modeling may also refer to the merging, synthesis and analysis of spatial patterns in order to obtain answers to specific questions.

In recent years, this latter form of spatial modeling has had several notable successes when applied to the coastal zone. Typical applications include: the use of GIS for assessing the threat of sea level rise on the coast of Maine and the likely responses of coastal sand dunes to such rise (Dickson et al., 1988); modeling of oil spills with a view to minimizing their environmental impacts (e.g. Kendziorek, 1989; August et al., 1990); modeling possible impacts of dredge spoil dumping (Bokuniewice et al., 1989; Hansen et al., 1990); modeling for multiple use of estuarine waters (Clark, 1990; Gardels et al., 1990; Hazelhoff and van Hees, 1991); and assessment of possible sites for aquaculture development in Costa Rica (Kapetsky et al., 1988).

However, GIS can also allow mathematical process models to be used in conjunction with spatial data models (as represented by matrices of raster data or topological vector data), in order to obtain the best of each. Bartlett (1989), for example, demonstrated that a linear wave energy refraction model written in the FORTRAN programming language could successfully be merged with a proprietary vector GIS package (ARC/INFO) allowing digital maps of wave energy distribution to be generated and related to the distributions of sediment size, beach morphology, and other coastal phenomena of interest.

Decision-making and policy formulation is clearly linked to the above. By combining rapid data retrieval with analytical functions, GIS have the ability to respond rapidly and flexibly to *ad hoc* "what if" type questions. A well-designed coastal zone information system could, therefore, be a significant technological contribution to development of integrated and sustainable coastal management. Numerous such systems have either been implemented or else are currently in various stages of development: Law (1991) and Coleman et al. (1991) discuss the benefits that GIS can bring to management of the Canadian Great Lakes shorelines of Ontario; Fairfield (1987) describes the use of GIS to plan marina developments; and Townend (1990, 1991) describes how a large GIS is being developed to aid management of the East Anglian coast of England.

Coastal Resource Survey and Management

We have already seen that a growing human population is making demands on the shore for living space, leisure and recreation, and a host of other purposes. At the same time, the oceans and coastal waters of the world are important source of fish and other food resources, as well as oil, natural gas, aggregates, manganese and a variety or other minerals. Thus, coastal management can be seen as a special category of resource allocation (Scalise and Bartlett, 1992; Bartlett et al., 1993). Frequently, GIS are used to assist in exploration and exploitation of these resources.

Within the leisure and recreation sectors, several examples exist where GIS have been used to good effect in the assessment, development and management of coastal resources. Examples include the siting of shore-based facilities such as marinas (e.g. Fairfield, 1987), and the management of recreation activities in areas of fragile coastal dune systems (McGrath, 1990), as well as in the management of coastal recreation in more general terms (e.g. Crandal, 1986).

The fishing and aquaculture industries have likewise looked to GIS to assist in various operations: for example Kapetsky et al. (1988) describe the use of GIS to locate fish farming activities through the analysis of salinity, bathymetry, shelter, landuses, proximity to other facilities, etc.; while Sharp et al. (1989) discuss the use of remote sensing and GIS to assess fishing effort in the Scotia-Fundy region of eastern Canada.

GIS are also a major technology within the mining and oil exploration industries where they are harnessed to assist in the discovery, assessment and exploitation of new mineral wealth. Unfortunately, many of these applications remain relatively undocumented for reasons of commercial confidentiality, but examples do appear in the literature from time to time. Jefferies-Harris and Selwood (1991), for example, have described the use of a commercial vector GIS product for the management of marine sand and gravel.

Other potential applications of GIS in the broad sector of resource exploration and management include the siting of landfalls for oil and gas pipelines, the analysis of seabed topography and geological structures to assess dredging/mining viability, etc.

Impediments to the Use of GIS on the Coast

The foregoing section has focused on real and potential ways in which GIS can be used within the coastal zone. However, it is axiomatic that decision-makers should be aware of the limitations and shortcomings of the techniques they are using, as well as knowing about the areas of potential success. Nowhere is this more relevant than when considering the application of the technology to the coastal zone. Although the use of Coastal Zone Information Systems (CZIS) is increasing rapidly, and the analytical powers of such systems are continually being extended, it must be emphasized that the unique character of the coastal zone presents certain inherent problems for database creation and analysis. Broadly speaking, these limitations arise due to problems of data availability, the geometry and physical characteristics of the coastal system, and the dynamic nature of the coastal environment.

Sources of Data for Coastal GIS

All GIS depend on data for processing: indeed, it has been estimated that up to 65% of the cost of any GIS application is accounted for in the capture of data. These data fall into two categories, namely the basic planimetric or locational data which define the position of coastal objects (beaches, plant communities, cliffs and dune systems, roads and settlements, etc.), and the corresponding attribute and descriptive statistics which tell us more about the properties of the entities that these represent (e.g. name of an administrative region, sediment characteristics of a beach, wave climate parameters, etc.).

Unfortunately, in most parts of the world both types of data are frequently lacking for coastal areas. It is surprising given our long association with the sea that the systematic collection of data relating to the coastal environment is only a feature of the present century. Some types of data are, of course, more important than others, and in some cases "gaps" in the available data set may be filled in part by interpolation from known datum points, or by ground survey. Nevertheless, there are many instances where either the required data are not available in any form, or else there are data available but at degrees of resolution or accuracy which are inadequate for the application in hand.

The consequences arising from such issues of data availability are not trivial. One particularly useful study in this context is that of Smith and Piggott (1987), who undertook a qualitative and quantitative assessment of the usable database for part of the coastal zone in Queensland, Australia. Having examined a wide range of physical and social parameters, they concluded that in some extreme cases the coastal manager has less than a 50% probability of making any correct decision, even when the results are based on the best information available.

One typical example where available data are normally inadequate would be the construction of terrain models to support analysis of flooding in respect to future sea-level rise. Even by the most extreme estimates sea level is unlikely to change in most areas by more than 3 meters over the next century or so (Titus, 1984, 1987). Nevertheless, the impacts of a sea level rise of even half a meter could be severe, particularly in such low-lying coastal areas as the east coast of the United States, or that of Bangladesh. Thus, assessment of the attendant risks is being carried out at a number of locations worldwide.

GIS is clearly a valuable tool in aiding such research, enabling the identification of vulnerable areas, and formulation of policies to deal with the anticipated problems. Often, such analyses make use of computer-held representations of coastal topography, known as digital terrain models (DTMs) or digital elevation models (DEMs). However, the digital terrain models (DTMs) required to support analyses of flood vulnerability typically focus on that part of the coastal zone lying within about 10 meters above or below mean sea level, and therefore need to be built from topographic data acquired at 1- or, at most, 5-meter intervals. Even within the more industrialized parts of the world, such as Europe and North America, there are very few areas where the coastal zone has been surveyed to this degree of vertical accuracy.

Nor is the lack of data merely confined to elevation and planimetric measurements. Attribute data, whether relating to sediment types and distribution, behavior of human visitors to the coastal zone, plant and animal distribution, or climatic conditions, are likely to be even more difficult to obtain, except by direct observation or measurement on a case-by-case basis.

Many efforts are being made worldwide to increase the available database, particularly regarding time-series data relating to meteorological phenomena, wave climate, and tidal regime. Such data are of extreme importance to civil engineers and coastal managers whose aim is the analysis of long-term trends and the recurrence of extreme events. A growing amount of data is becoming available for such studies (e.g. Birdwell and Daniels, 1991), although there is a need for a certain degree of caution in interpreting results of analyses based on such information.

The relevant data needed for time series analysis have rarely been collected for more than a century even in relatively well-studied parts of the world such as Europe or North America. Thus the data may not be adequate for constructing statistically valid models. Occasionally, it has been possible to extrapolate backwards from recorded data through a process known as "hindcasting." This method has been used to expand the time-series of available data relating to waves and storm frequencies (e.g. Hubertz et al., 1991). However, while such data greatly enhance the range of research, it must always be borne in mind that they are themselves derived from processes of interpolation and extrapolations. Despite these caveats, it is likely that use of such data will become ever more common, as our understanding of coastal morphodynamics increases.

There is one important exception to this rule however, and this concerns the availability of remotely sensed data from airborne and space-borne platforms. It is a paradox frequently encountered in spatial information processing that while primary (in particular geodetic and topographic survey) data are generally in short supply, and can thus constrain the implementation of GIS, remotely sensed data are now extremely abundant and the sheer volume and available range of such data can at times be bewildering.

Since the 1970s, a number of satellites (notably the Nimbus 7 Coastal Zone Color Scanner and, more recently, the Landsat and Spot series of platforms) have been launched, in which coastal observation has been an important, or even the primary, objective. Mitchener et al. (1989) give an excellent review of the potential of remote sensing, combined with GIS, for coastal research. More recently, video imagery captured from airborne platforms has also been used for coastal applications (e.g. Everitt et al., 1991; Debusschere et al., 1992), and looks to become an important future source of thematic data on the coastal zone. Images from all of these various sources have greatly extended the potential of GIS for coastal purposes, and a number of exercises in this workbook demonstrate how such data may be incorporated into a GIS-based study.

Data Modeling Issues

One of the basic tenets of good database design is that, long before the data may be entered into the computer, a careful process of data modeling and structuring is necessary. The ultimate objective of this exercise is to somehow reduce the multi-dimensional complexity of the real world into a form which may be stored in one-dimensional computer memory (Peuquet, 1984). As Peuquet (1984) states, "...no model or abstraction of reality can represent all aspects of reality [so] it is impossible to design a general-purpose data model that is equally useful in all situations."

The rationale for, and the actual steps involved in, data modeling have been thoroughly discussed in most standard texts on GIS (e.g. Burrough, 1986b; Aronoff, 1989), and need not be discussed here. However, the importance of careful data modeling, before any attempt is made at creating the database, cannot be over emphasized. As Smith and Piggott have stated, the degree of success with which any spatial information retrieval, manipulation and analysis can be accomplished "is determined by the data models, data structures, algorithms and database management techniques selected for the GIS" (1987, p20). These observations are particularly appropriate with regard to the design of coastal zone information systems, and Bartlett (1989, 1990) suggests that much of the failure to implement effective, powerful GIS on the coast, comparable to those routinely used in many terrestrial applications, may be due to the lack of suitable data structures for representing the complexity of the coast in one-dimensional computer storage.

Two generic approaches to spatial data handling may be recognized, namely the vector and the raster data models respectively. While both have their own distinctive set of strengths and weaknesses with regard to coastal data, neither is ideal.

The Vector Model for Coastal GIS

At first sight, use of a vector-based approach to coastal GIS has considerable appeal largely due to the common (though over-simplistic) perception of the coast as a fundamentally linear entity (e.g. Weyl, 1982). Thus, examination of the literature (Bartlett, 1990, 1993) shows that many early attempts at applying GIS to coastal issues were based on vector data: a typical examples is the Research and Management Shoreline (RAMS) Database (Eberhart, 1980; Eberhart and Dolan, 1980), one of the earliest documented systems for coastal management to provide details of the underlying data format. The RAMS database used unstructured, "spaghetti" vector data to provide a visual backdrop for data collected and displayed as point objects.

More recently, a growing number of GIS implementations for coastal purposes have been based on modern, topologically-structured vector systems. Examples, some of which have already been described above, include the use of ESRI's ARC/INFO system to assess vulnerability to sea-level rise (Gornitz et al., 1991), aid management of marine sand and gravel extraction (Jeffries-Harris and Selwood, 1991), and assist in coastal wetland management (Schauser et al., 1990; Somers et al., 1989). Similarly, Intergraph GIS products have been used to develop shoreline protection strategies in East Anglia, England (Townend, 1990, 1991), and have been used to analyze shoreline changes over time in Florida (Demirpolat et al., 1989) and in Louisiana (Debusschere et al., 1992) amongst other applications.

While the representation of the coast as linear data objects seems to dominate, topological vector systems are not limited to such a model. They can, and frequently do, also use point and area (polygon) data objects, surface modeling, and digital terrain analyses as appropriate. Clearly, use of this expanded range of spatial data objects increases significantly the analytical and integrative capabilities of the coastal GIS application. However, this also raises complications. In particular, it should be noted that many phenomena within the coastal zone are more correctly demarcated by zones of transition and gradients, rather than by any well-defined or static boundaries.

Unfortunately, current GIS, and commercial vector systems in particular, are still very poorly suited to handling such "fuzzy" data. Thus, it may often be necessary to interpolate ranges and surfaces from (often sparsely-distributed) point data, and to assign more-or-less arbitrary boundaries to certain phenomena. While necessary, such steps may significantly increase the degree of uncertainty and/or potential error in any resulting analyses based on these input data (more comprehensive discussions of error and uncertainty issues in GIS are provided, e.g. Burrough, 1986a, 1986b; Chrisman, 1991).

Use of a vector data model also fails to address problems of variable spatial resolution of coastal data. It is well known that as the scale of any coastal study increases the amount of detail that emerges increases: in other words the coastline is the classic example of a geographical feature possessing a fractal dimensionality (Mandelbrot, 1967; Kappraff, 1986; Goodchild and Mark, 1987).

Concepts of fractal geometry may be of use in coastal contexts for their ability to predict the relationship between scale changes, line generalization and spatial sampling (Goodchild and Mark, 1987) and for assessing the affinity between a model and the real world phenomenon that it seeks to represent. It is important nevertheless to note that fractals only work with statistical probabilities and therefore cannot (at least under present states of knowledge) be used to add detail to simple representations of the coast. Nor is the author aware of any applications of fractal geometry implemented as yet within a GIS framework. However, this is an area ripe for scientific investigation, particularly when attempts are made to classify coasts according to morphological characteristics.

However the geometry of the coast is defined, any application of GIS which seeks to permit modeling or analysis of shoreline phenomena has, almost by definition, to address problems of data capture density. This incorporates such questions as which points along the coast are to be considered significant, and how frequently are data points to be recorded? In practice, data will normally be captured at the highest level of resolution required for any specific purpose and subsequently generalized and/or simplified where less precision is required (e.g. Douglas and Peuker, 1973).

Vector Models and Recursive Decomposition Methods

An alternative approach to problems of line detail and spatial resolution lies in the use of recursive methods of decomposition of space. This involves breaking down a geometric unit into smaller sub-units in a hierarchical fashion until the desired level of resolution has been attained. Unlike applications of fractal geometry, methods of recursive decomposition of space have been studied in a GIS context for many years, particularly in the form of hierarchical nestings or quadtrees (Morton, 1966; Mark and Lauzon, 1984; Peuquet, 1984; Buttenfield, 1985).

Recursive decomposition techniques are most commonly encountered in the context of tesseral data, and these will be returned to below. However, they may also be applied to linear entities, and a number of examples of this approach may be encountered when considering coastal GIS. One early example of the application of decomposition techniques to a vector-based coastal GIS was seen in the Canadian Coastal Information System (CIS) initiated by the Geological Survey of Canada in 1982 (Fricker and Forbes, 1988). The data storage model used within CIS was still based on the one-dimensional line, but the CIS attempted to get around some of the problems of scale difficulties by dividing the coastline of Canada into arbitrarily-chosen "segments of convenience", which were "as long or as short, as comprehensive or as detailed as required" (Fricker and Forbes, 1988, p113). Each segment was recorded as a straight line defined by its two end nodes with features and attributes specifically assigned to relevant segments. However, it is important to note that the decomposition of the coast within CIS was done on purely subjective criteria.

A similar technique of dividing the coast line into segments has been recorded by Debusschere et al. (1992). In their analysis of changes on the coast of Louisiana, the authors mapped shoreline attributes onto a linear, ribbon-like representation of the coast which could then be unfolded and stretched out for visual or analytical assessment of changes between successive time periods.

Recently, a new technique of decomposition of the line has emerged. Known as dynamic segmentation, this approach was developed originally within transport studies and routeway analysis. Dynamic segmentation allows line objects to be defined according to arbitrary start- and end nodes with attribute data linked to arbitrary segments within the line. Perhaps because of the comparative novelty of the technique, the literature does not yet record examples of dynamic segmentation being used for coastal applications of GIS. Nevertheless, the concept is currently being investigated in at least one institution (Scalise and Bartlett, 1992), and further applications may be confidently predicted in the not-too-distant future. Preliminary results suggest that as a means of dividing linear objects and comparing variables attached to such objects it is a technique with considerable potential.

Tesseral Data Models for Coastal GIS

The word "tesseral" comes from the Latin "tesserae", which means "tile", and describes the representation of geographic space as a mosaic of small cells. Tesseral data handling methods are used primarily with contiguous data; the aim being to divide continuous space into regular, isohedral, unlimited and, preferably, recursively-divisible tilings or tesselations (Bell et al., 1983; Diaz and Bell, 1986). In theory, there exists a total of 81 possible isohedral tessalations of the plane (Grunbaum and Shephard, 1977), but in practice the most frequently encountered tessellation for geographical data handling remains based on the rectangular grid. It is the tiling system used by many commercial and non-commercial GIS packages (including IDRISI and the public domain system GRASS), and, as far as can be established, this is the only configuration to have been used in a coastal context to date.

The advantages of the square, or rectangular, grid for geographical data processing are well known (e.g. Burrough, 1986b; Berry, 1987), and many of these advantages apply to coastal GIS applications. They include the long history of the use of rectilinear grids within conventional cartography; the ease of translating the matrix into one-dimensional computer storage; the growing quantities of remotely sensed data that are captured, transmitted and stored in raster format; and, increasingly, the number of simulation software programs for modeling coastal processes that are based on rectilinear matrices. In addition, it may be noted that in the raster model the primary emphasis is on analyses of continuous space, and boundaries between zones are implied rather than being defined explicitly. Given the difficulties of identifying clear boundaries within the coastal zone, as was discussed above, this suggests a clear advantage in using the raster model for coastal studies. However, against this are a number of equally clear disadvantages, including those of data resolution and storage volumes (which will be discussed again below). In addition, raster systems often lack the finer drafting and cartographic capabilities present in most vector systems.

One early application of a gridded data model to coastal information arose from the University of Edinburgh's Tourism and Recreation Research Unit's Coastal Habitat Monitoring Project (TRRU, 1977). This project included the capture of Scottish coastal data from maps and air photographs on a 1 km grid basis; the creation of a digital database; and analysis of the data and output of information in tabular and cartographic form. More recently, Foley (1991) has described the use of IDRISI to create a digital terrain model of an area of sand dunes in Ireland and subsequently to model vegetation and other variables affecting the dune system dynamics.

Tesseral Models and Recursive Decomposition

Despite their advantages, any gridded data can occupy inordinate volumes of computer storage. Given the large areal extent of many, if not most, coastal studies and the levels of cell resolution that would be required for meaningful study, such data volume issues can be particularly critical within a coastal GIS. While a number of solutions have emerged to these problems, such as data compaction through run-length encoding, by far the most promising from the point of view of coastal applications of GIS is the use of techniques for recursive decomposition of space (quadtrees and, for studies based on digital terrain models, octrees). Only one commercially-available GIS (SPANS) currently uses the quadtree data structure for raster data, and this system has been applied in a number of coastal studies (e.g. Coleman et al., 1991; Devoy and Bartlett, 1991).

The advantages of the quadtree structure are based on speed of processing and display, so quadtree systems are most likely to be used where there is a demand for real-time modeling and retrieval of data. Furthermore, techniques of recursive decomposition of space should allow the greatest amount of attention and detail to be devoted to where it is most needed (the actual zones of contact of land, sea and air) and would also reduce data volumes and the likelihood of data redundancy. As distances away from the shoreline increase, the size of the quadded blocks could be similarly increased, since (particularly in a seaward direction) greater homogeneity of features would been countered.

Against this, it may be noted that hard copy output from most quadtree (and, in fact many conventional raster) systems is generally considered less good than that from comparable vector systems. In addition, it is also unclear how to translate dynamic coastal process models based on regular grids, such as those mentioned above, so that they can work within a variable-resolution matrix.

Conclusion

Irrespective of the basic data structure adopted, the coastal zone is an inherently difficult system to model because many coastal phenomena have very poorly-defined boundaries. Sediment types, for example, can often grade imperceptibly over space from one category to another with no obvious point of transition. The dynamics of the coastal system, referred to above, are equally important in this context: to take a seemingly trivial example, how does one represent the position of the land/sea interface on a map if the line in question is constantly moving?

In practice, many applications of GIS will adopt a similar approach to that used by more traditional cartographers whereby the position of the shore is determined according to some arbitrary criterion (e.g. selection of mean sea level, or some other position of the tides, as a standard datum level). Other phenomena, however, may be less easy to model, and it may sometimes be appropriate to seek solutions based on fuzzy logic or probabilities of occurrence (Burrough, 1986b) rather than on "absolute", or Boolean, logic.

With growing pressure on the shore and increasing environmental concern being voiced an increasing number of coastal-oriented GIS applications are emerging. Most of these are based on the use of proprietary GIS packages. However, as has been outlined in this article, the coast has unique attributes and properties, and it is questionable whether currently-available commercial GIS products are optimally configured to handle coastal data. While there is no doubt that such systems are being, and will continue to be, adapted to coastal data (or, more dangerously, coastal data are being "shoe-horned" to fit the requirements of the technology), in the longer term successful implementation of coastal GIS requires new concepts and approaches to be developed.

Because of the growing importance of sound, integrated coastal management and the attendant need for efficient means of handling large quantities of spatially-referenced coastal data, in 1990 a working group of the International Geographical Union's Commission on the Coastal Environment (superseded since August 1992 by the IGU Commission on Coastal Systems) was established specifically to promote the optimum use of GIS for the coast.

Much work in this area remains to be done, however, and coastal GIS still offers many exciting challenges. Given the fundamental nature of some of the issues concerned, it appears that overcoming the hurdles will often require a return to first principles and re-examination of certain key paradigms of spatial science and GIS. Perhaps paradoxically, in seeking answers to these various conceptual and design questions, it may be suggested that relatively simple but robust systems such as IDRISI, in the hands of new researchers, will stand as much chance of success as will more complex systems and older-established investigators.

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Exercise 1: Coastal Fisheries Management—Shrimp Habitat Analysis in Southwest Florida

One of the most basic components of coastal fisheries management is the inventory of resources. It is vital for managers to know the quality and extent of resources if they are to effectively advise both the coastal fishing industry and environmental regulators. Unfortunately, resource data collection for the coastal zone has been scant, and this has caused spatial analysis to be limited. However, as data becomes less expensive and more often available in digital format, basic GIS tools can be employed to make sound management recommendations.

This exercise will reacquaint the user with basic GIS techniques in the context of coastal fisheries management. It will illustrate the usefulness of data query and overlay to analyze local fishing industry practices and their potential impact upon fisheries resources. In particular, we will examine the shrimp industry and the coastal environment in the Tampa Bay area of Southwest Florida. It should become clear that with the use of GIS there is a surprisingly wide range of questions that can be answered using easily obtained information.

The shallow waters of Tampa Bay, particularly those that have a thriving seagrass environment, are important breeding and nursery areas for the fish and shrimp that support the region's fishing industry. While many factors determine the viability of these areas, our exercise will only examine three. Because local seagrass environments are vital to the regional fishing industry, the extent of seagrass coverage will be the first important piece of information for our analysis. However, we must also account for the pressures both within the fishing industry and without that are threatening these rich nursing grounds. For example, it is known that current shrimp trawling practices can cause considerable damage to seagrass ecosystems and finfish nursery populations. Food shrimp trawling (as opposed to bait trawling) utilizes large and heavy trawls that can destroy seagrass habitats. In addition, studies have shown that for every pound of shrimp caught in seagrass areas, ten pounds of juvenile finfish are killed and discarded (i.e. the bycatch) (Fitzgerald, 1992). Clearly, knowing the extent of shrimp trawling will also be important to our analysis. Finally, because shallow water seagrass habitats are more likely to contain young shrimp and fish than deep water, bathymetry data will also be needed.

While data on seagrass, bathymetry, and shrimp trawling extent is easily available and valuable to our analysis, we should also clearly point to their shortcomings. Changes in the quality of the seagrass environment should not be seen as solely the result of this one process, shrimp trawling. A variety of processes that have accompanied the rapid population growth and development of south Florida have also contributed to the decline of these environments. An effort should be made to incorporate them into the GIS as well. However, this exercise will focus solely on data and information made available through the Florida Marine Research Institute.[1]

In 1990, the Florida Marine Fisheries Commission began to develop a statewide shrimp management plan. Two key management options that address shrimp bycatch and habitat impact problems are proposed for incorporation into this plan—the first is the use of finfish excluder devices (FED) designed to cut down on bycatch during shrimp trawling, and the second is area closures. Both of these regulation options could benefit from even the most basic spatial analysis.

In this exercise, the available data on seagrass, bathymetry, and area of shrimping will be combined and explored in a GIS to locate areas thought to be biologically very productive and vulnerable to damage by shrimping practices. Given a real management situation, we might suggest that some of these areas be closed to shrimping or, perhaps, be limited to shrimping using only FED technology. This exercise will consist of three parts. In the first part we will create a bathymetric surface from a sample of depths. The second part will concern resource inventory. There we will calculate the areal extent of seagrasses and analyze its relationship to water depth. The final part will incorporate some general data on shrimp fishing. Also, as noted previously, this exercise is intended to be a refresher in the basic tools of geographic analysis.

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Part 1: Create a Bathymetric Surface

Data Exploration

We will begin by examining the seagrass habitat and shrimping area data layers.

a) First, open IDRISI and under the File menu, select IDRISI Explorer. Then select it's Projects tab. This option allows you to set the project environment of your file folders. Make sure that the Editor pane is open at the bottom of the form. If you right-click anywhere in the Projects form, you can select to show the Editor. The Editor pane shows the Working and Resource folders. Choose to either create a new project or edit the existing project to include the folder holding the data for this exercise, (e.g., c:\UNITAR\CZ\Data\Exer1). Please note that this folder must be listed as either the main Working folder or one of the Resource folders. Then open the User Preferences dialog from the File menu and click on the Revert to Defaults button, then click OK. This will turn on the automatic display of module output with legend and title options.

b) From the Display menu, click on DISPLAY Launcher. Choose to display a raster layer, then either click on the browse buton at the right side of the file input box or double-click in the input box to bring up the pick list. Choose the image file HABITAT. Note that the HABITAT palette is automatically selected. Accept the rest of the default settings and click OK to display the raster image.

c) Follow the same procedures to display the image SHRIMP. This time, the Qualitative palette is automatically selected.

Now from the Files tab of IDRISI Explorer, access Metadata to examine each image. If the Metadata pane is not in view at the bottom of the form, right-click anywhere in IDRISI Explorer and check that Metadata is selected.

HABITAT: A raster image of the marine habitat for the area, showing density of seagrass cover, interpreted and digitized from 1988 aerial photographs.

SHRIMP: A raster image of shrimping areas, as defined by shrimpers on nautical charts.

The third data layer, bathymetry, will be constructed as part of this exercise from two separate vector files.

d) Open DISPLAY Launcher and select the Vector layer option. Enter the filename DEPTHS and press OK, accepting the default settings to display its contents. Follow the same steps to display the vector file COASTLINE. Then use Metadata to examine the documentation for each vector file.

DEPTHS: A point file of soundings measured in feet digitized using the NOAA nautical chart for St. Petersburg, Florida.

COASTLINE: A line file representing the coastline for the study area.

Data Integration

e) Close all display windows except for HABITAT. Click on the Add Layer button in Composer and choose to add the vector file DEPTHS. An error message appears, telling you that the reference system of DEPTHS does not match that of HABITAT. While DEPTHS is listed on Composer, it is not visible in the display. To see why, display the vector file DEPTHS with DISPLAY Launcher. Move your cursor to the center of the DEPTHS map display and note the X and Y coordinates listed at the bottom of the screen. Click on the HABITAT display and again move your cursor to the center of the image and note the X and Y coordinates.

1. *Are the coordinates at the center of the maps similar or different?*

f) Using IDRISI Explorer's Metadata option, note the reference system used for the HABITAT and SHRIMP images. Then view the metadata for the vector files DEPTHS and COASTLINE.

2. What reference system is used for each of the four data layers supplied? To perform virtually any GIS operation, what must first be done to this data set?

A reference system includes a projection, datum, origin, coordinate system and other information. (Consult the Georeferencing chapter of the IDRISI Manual found in the IDRISI Help System for more information on reference systems.) The two raster files in this data set use a different reference system that has a very different coordinate system than those used by the two vector files. To be able to use these data layers together in any analysis, they must be brought into a common reference system. We will change the vector layers to match the raster layers.

To change the reference system of the coastline and depth data we will utilize the PROJECT module. This module is designed to re-project either a raster or vector data file from its current coordinate system and projection to another coordinate system and projection. In order for the module to convert systems, it uses reference system parameter files (one for each reference system). Hundreds of these files are provided with IDRISI. When data is acquired, it is important to determine which existing reference file matches the new data layer. Documentation (metadata) that accompanies the data layer should include all the necessary information.

In this case, the vector layers are in the Florida State Plane Coordinate System and all the parameters of that system match the reference file SPC27FL2 that is supplied with IDRISI. The raster layers, however, are in a reference system for which no file is supplied. To make use of this data, a new reference system was created using the Metadata facility in IDRISI Explorer. The new system is called UTM17FL and the reference system parameter file is included in your data directory. It is identical to the supplied file US27TM17, except the Molodensky values are those used for the eastern US rather than the entire conterminous US.

g) Using Metadata, view the documentation for Reference Files (.ref) (make sure Reference (*.ref) is selected in the Filters tab so this type of file will be listed in the Files tab) and examine the file UTM17FL in your data directory. This is the reference system used by the raster layers in this data set. Then choose the file SPC27FL2 from the Georef folder found in your IDRISI application folder.

This is the reference system used by the vector files. There are several differences between the two reference systems. Note the nature and amount of information you need in order to properly convert a data set from one reference system to another. Clearly, it is important to know where data comes from in order to document this appropriately.

We will run PROJECT, once for each vector file, converting the files from Florida State Plane to UTM coordinates.

h) Run PROJECT from the Reformat menu. Specify vector as the type of file to be converted and DEPTHS as the input file. The current reference system, SPC27FL2 will appear automatically. Enter DEPTHUTM as the output file, and select UTM17FL as the output reference system parameter file. Click OK.

i) Run PROJECT a second time, specifying a vector file conversion. Select COASTLINE as the input file and call the output file COASTUTM with UTM17FL as the output reference system.

j) To see where the re-projected soundings and coastline are located, use DISPLAY Launcher to view HABITAT. From Composer, select Add Layer. Enter COASTUTM and click OK, accepting the Standard default symbol file. Add a second layer called DEPTHUTM by selecting Add Layer again. Use the remaining defaults to overlay this point file.

While the composition is very crowded, it does give an indication that our coordinate systems are now the same. You should also notice some slight discrepancies between the coastline in HABITAT and COASTUTM due to the fact that they come from different sources. This should not significantly affect our analysis.

Building a Bathymetric Surface Model

It is important to note that coastal zone bathymetry is essential to most coastal zone studies and that there are a number of ways in which to obtain such information. Digitizing nautical charts is clearly the most accessible. However, the coastal zone changes rapidly making reliability of such data questionable. Also, many coastal areas of the world have not been surveyed to the extent needed, and good maps are not available for digitizing. There are, however, other methods to acquire bathymetric data; methods inherently compatible with GIS technology. For example, direct field measurements in conjunction with a Global Positioning System hand-held recorder (GPS) make frequent surveying faster and relatively less expensive. Soundings and their GPS coordinates are easily transferred to many GIS systems. In addition, remotely sensed imagery from Landsat satellites or aerial photography can be used in GIS systems with image processing capabilities to roughly gauge water depth. These methods, clearly important to coastal zone research, will be discussed in later exercises.

To build the bathymetric data layer for this exercise, we will interpolate (i.e., estimate unknown depths based on known depths) a surface using converted coastline and depth data. The result will be a raster image where the value of each pixel represents interpolated bathymetry.

It would seem that simply interpolating between the soundings alone would be the most straightforward way to create a continuous bathymetric surface. However, interpolation in the case where a shoreline is involved would result in values near the shore that are unlikely in reality. That is, the interpolated surface does not account for land areas because we have no control points on land, and if we simply mask the land in a later step, we may find bathymetry sloping downward toward shore! Consider the case of a narrow spit of land with a sounding of 5 feet on one side and 20 feet on the other. There will be a continuous slope downwards from 5 to 20 irrespective of where land will fall in any later overlay. In fact, without control points where depth equals zero (i.e. along the shoreline), the interpolation routine will produce a surface that does not consider land at all.

To account for the shoreline, we will convert the coastline file to a point file, combine these points with the file of points representing depth, and then interpolate a bathymetric surface with land equal to zero depth. There are several steps required to create the combined shore-depth point file. These have been done for you and the resulting vector file is in the data set. We will use a Triangulated Irregular Network (TIN) interpolation technique to create the raster bathymetric surface.

k) Display the vector file ALLPOINTS.

This was created with the following steps:

The module TINPREP was used to add more points along the coastline such that a point exists at least every 2 meters. This was done to ensure that in the triangulation, land areas would always be flat and have the value zero.

The module LINTOPNT was used to change the COASTLINE line file to a vector point file.

The new COASTLINE vector point file and the DEPTHS vector point file were combined using the CartaLinx vector editing and digitizing software (also developed by Clark Labs) and then reimported to IDRISI. The resulting vector point file is ALLPOINTS.

l) Use Cursor Inquiry Mode from the toolbar (the icon with a question mark and arrow) to explore some of the sounding point values. Note as well that all coastline points have the value 0.

m) From the GIS Analysis/Surface Analysis menu, choose the TIN module. Select the points option, then enter ALLPOINTS as the input vector file and TIN as the output tin file. We will create a raster surface at this time as well, so enter BATHYMETRY as the raster surface image to be created following the creation of the TIN file.

n) The resulting TIN image showing the triangulation will not automatically display. You may look at this file by using DISPLAY Launcher to display the vector file TIN. You will see that triangle vertices are located at the points of the ALLPOINTS file. (The TIN chapter in the IDRISI Manual explains the TIN procedures in detail.)

The module used to create a raster surface from a TIN is TINSURF. It creates a raster image with the same extent as the TIN vector file. Since we indicated we would create a raster surface image, the TINSURF module interface is automatically displayed with information about the files and specifications. Before running TINSURF, we will copy the specifications from an existing raster file in our data set, HABITAT, so that we guarantee that the extent of the TIN file matches that of the other raster images (such as HABITAT) in the data set. We will want to use the three raster images together, and for this to be possible, they must have the same number of rows and columns and the same extent.

o) Open TINSURF from the GIS Analysis/Surface Analysis menu, select Copy from existing file, and type in or select the file HABITAT. The parameters from the HABITAT file will be automatically displayed. Then enter 0 as the background value for areas that fall outside the TIN. Click OK and the surface image will be generated.

3. Where might errors have been introduced in the creation of our bathymetric model? How might we correct for them?

To better visualize the bathymetric model, we can display it in orthographic perspective using the module ORTHO.

p) Run ORTHO from the Display menu and specify BATHYMETRY as the image to be displayed. Uncheck the drape image option and change the viewing angle to 35. Specify an output resolution that is one step smaller than your screen resolution and accept the rest of the default values. (If you are unsure of your screen resolution, choose 800 x 600 or 640 x 480.) When the image displays, you may wish to use the Maximize Display of Layer Frame icon on the toolbar (7th icon from left) or simply press the Home key.

4. How might this image be useful for analysis? Run ORTHO again and this time, drape the image HABITAT over the bathymetric model, change the viewing angle to 35, and use the HABITAT palette. What is immediately evident?

The ORTHO results may lead us to ask, "What is the average water depth for each of the HABITAT classes?" Now that we have a complete bathymetric surface, we can easily calculate the values as well as the other summary statistics using EXTRACT.

q) Run the module EXTRACT from the GIS Analysis/Database Query menu. Use HABITAT as the feature definition image, BATHYMETRY as the image file to be processed, average as the summary type and tabular as the output type.

5. What are the average depths for each of the seagrass categories?

Now that all of the three data layers discussed at the beginning of the exercise are available, we can proceed to the next sections on resource inventory and shrimping activities analysis.

Part 2: Fisheries Resource Inventory

In this section, we will calculate the areal extent of seagrass habitats, reclassify the bathymetry data to a discrete number of classes, and examine areas that are interesting combinations of both the seagrass and bathymetry data sets. In particular, we will highlight dense seagrass areas in shallow water because they are the most biologically productive, and they act as nursery areas for a variety of commercial fish in this region.

Calculating Areal Extents

First, we will create a new image showing only seagrass areas. To do this we need to renumber the seagrass categories in the image HABITAT and assign all other categories the value 0. The modules RECLASS or Edit/ASSIGN could be used. Here Edit/ASSIGN will be illustrated. ASSIGN assigns new integer or real values to a set of old integer data values. First we need to create a new attribute values file that lists the new assignment for the data values. Data values that are not mentioned in the reassignment are automatically assigned the new value zero. You can learn more about the difference between RECLASS and ASSIGN in the IDRISI Help System.

r) Run Edit from the Data Entry menu. Type in the two columns of values as follows with a space between them.

4 1

5 2

6 3

s) These values indicate that the "old" habitat categories of 4, 5, and 6 (sparse, patchy, and dense seagrass) will be reassigned to the new categories 1, 2, and 3 respectively. Under the File menu on the Edit dialogue box, choose Save As. Enter the name SEAGRASS and choose Attribute Values File (.avl) as the file type. Click Save and choose integer when asked for the data type. Close Edit.

t) Now run ASSIGN from the GIS Analysis/Database Query menu. Specify HABITAT as the feature definition image and SEAGRASS as the values file. Call the new output image SEAGRASS (an image file can have the same name as a values file because they will have different extensions).

u) *Optional Step.* You may wish to create your own palette for this image using Symbol Workshop under the Display menu. Open Symbol Workshop and in it's dialog box, select File/New. Choose to create a palette file called SEAGRASS. To change a palette color, click on the color box then choose the new color. The SEAGRASS image contains values 1, 2 and 3, so you need only define those colors in the SEAGRASS palette. When you have finished choosing colors, select Save from Symbol Workshop's File menu and close Symbol Workshop. To apply this new palette to the displayed SEAGRASS image, click on Layer Properties in Composer and enter SEAGRASS as the palette.

The next step is to calculate the areas of the different seagrass classes. The area covered by different densities of seagrass is vital information for fisheries management. Future surveys (or historical surveys such as old aerial photographs that have been reinterpreted) can be compared to this data set. The comparison potentially reveals changes in the quality and quantity of seagrass habitats.

v) Run AREA from the GIS Analysis/Database Query menu. Choose tabular output, specify SEAGRASS as the input file and use hectares as the unit type.

6. What is the area of each seagrass class? Could we have found these figures without first reassigning the categories of the habitat image?

Seagrass and Bathymetry Analysis

We have already looked at the general relationship between seagrass type and bathymetry in the orthographic view. However, we will now look at this more closely by reclassifying the continuous bathymetry surface previously created into discrete categories, each representing a range of depths. Then we will mask the areas known to be land. The resultant categories will be land, water that is less than 3 feet deep, water between 3 and 6 feet deep, and water deeper than 6 feet deep. To create a new image showing these categories we will use the images BATHYMETRY and HABITAT.

7. Why not use continuous data? Why not use the module ASSIGN again?

w) First run RECLASS from the GIS Analysis/Database Query menu. Accept the default settings to reclassify an image and use a user-defined classification type. Choose the input file BATHYMETRY and call the resulting image TMPCLASS. Assign a new value of 1 to all values ranging from -3 to those just less than 1 (letting land temporarily become part of this category), a new value of 2 for all values ranging from -6 to those just less than

-3, and a new value of 3 for all values ranging from -999 to those just less than -6 (a number higher than the greatest depth in the image).

The land areas in the image BATHYMETRY should all have the value 0 in the TMPCLASS image. However, because the interpolation may have produced other non-land areas with the value 0, we will use the HABITAT image to define land areas. We will create a Boolean image in which land areas have the value 0 and all other areas have the value 1. When this is multiplied with the bathymetry categories image, land areas will take on the value 0 while all non-land areas will retain their bathymetry category.

x) Create a Boolean image in which land areas have a value of 0 and all others have a value of 1. Call the image TMPMASK.

8. Describe the method you used to create TMPMASK.

y) The last step is to make all the land areas in the categorized bathymetry image equal to zero. Run OVERLAY from the GIS Analysis/Database Query menu. Specify TMPCLASS as the first image, TMPMASK as the second image, and call the output image BATHCATS (bathymetry categories). Choose the multiplication operation. Change the display to use a qualitative palette or the SEAGRASS palette made earlier.

z) Use Metadata to update the legend categories of BATHCATS. Click on the Categories option in Metadata to launch the Categories form and add four legends. Use codes 0, 1, 2, 3 and captions of land, 0-3 ft, 3-6 ft, and 6+ ft, respectively. Save the changes, then redisplay the image to see the new legend information.

We will now examine the relationship between different densities of seagrass cover and water depth. Two related methods to do this are cross-tabulation and cross-classification. In the former, categories of one image are compared with those of a second image and a tabulation is kept of the number of cells in each combination. The table can then be used to easily calculate the relationships that exist between seagrass and water depth. In the later method, an image is prepared which shows the locations of all combinations of the categories in the original images. Areas of interest, such as shallow areas with dense seagrass, can then be mapped for use in fisheries management or further research.

Both of the above operations are accomplished in IDRISI with the module CROSSTAB.

aa) Run the module CROSSTAB from the GIS Analysis/Database Query menu with SEAGRASS as the first input image and BATHCATS as the second input image. Specify that you want a full crosstabulation table output type. Do not choose the Kappa option. The printed tables accurately show the relationship between water depth and seagrass that we saw earlier in the orthographic projection. The first table represents numbers of cells in each of the crossed categories while the second table represents proportions of the total in each of the crossed categories.

9. What percentage of the seagrass is in shallow (0-3 ft) water?

The results of the crosstabulation have given us a clear indication of the relationship between seagrass and water depth. However, it has not made clear the spatial extent of different cross-categories, nor has it directly provided a measure of area for them.

ab) Run CROSSTAB again with the same input files and this time choose to create a cross-classification image called GRASSBATH. In the output image display, note that each category in the legend has a caption that indicates the combination of categories from the original images in the same order as they are listed in the image title. To better examine the cross-categories, zoom in and out and pan across the image.

The cross-classification image can tell us much that the cross-tabulation cannot. For example, a visual inspection clearly shows that shallow water areas without seagrass tend to be those that are either the least sheltered or nearest to the developed part of the bay. The image also lets us consolidate cross-categories into a new image depending on our objectives. We will produce a hypothetical image of management classes, categories that might be used in fisheries or coastal management.

ac) Look again at the legend from GRASSBATH and fill out the following table. This information will be used to create a new image of management categories, called MANAGECATS.

Management Category	Description	GRASSCATS Category
0	land	
1	very vulnerable (dense seagrass and 0-3 feet deep)	
2	vulnerable (patchy and sparse seagrass and 0-3 feet deep)	
3	low threat (any seagrass and >3 feet deep)	
4	no threat (no seagrass and any depth)	

ad) Run Edit to create a values file called MANAGECATS where the old categories of GRASSBATH are in the left-hand column and the new categories to which they will be reassigned are in the right-hand column. Run ASSIGN with GRASSBATH as the feature definition file, MANAGECATS as the new image to be produced, and MANAGECATS as the attribute values file.

ae) Now let's calculate the areas corresponding to these four categories. Run AREA from the GIS Analysis/Database Query menu on MANAGECATS, specify tabular output and hectares as unit type.

> 10. *What is the area of the most vulnerable seagrass category? What is the total area of both vulnerable categories? Would this knowledge lead you to reclassify your results in another way?*

Part 3: Shrimping Activities Analysis

As mentioned above, seagrasses provide highly productive ecosystems that serve as nurseries for shrimp and different species of fin fish. Also, it is known that they are dragged for shrimp and that this practice is damaging. However, to what extent are they shrimped? Which of our management areas are shrimped and which are not? Fortunately, we have available a binary image that shows areas that are shrimped. This image, SHRIMP, was produced by shrimpers who outlined their fishing grounds on nautical charts. We can add this information to our analysis by cross-tabulating and cross-classifying SHRIMP with MANAGECATS.

af) Run the module CROSSTAB with MANAGECATS and SHRIMP as the input images and choose to produce both a cross-classification image and a crosstabulation table. Call the new image MANAGESHRIMP.

> 11. *Examine the crosstabulation table. What percentage of the most vulnerable management category is shrimped?*

ag) Interpret the legend of the MANAGESHRIMP image and determine which new categories represent areas that are shrimped. Then run the module AREA with MANAGESHRIMP and ask for tabular output in hectares.

> 12. *What is the total area shrimped in Tampa Bay? If shrimping was eliminated in the most vulnerable management areas, what percent of the areas now shrimped would remain?*

Summary

In this exercise, we first built a bathymetric surface model for a set of soundings stored as point data. Using this bathymetric model with habitat information originally from aerial photographs and shrimping data from local fishers, we then produced a series of cross-tabulations and cross-classifications. These results demonstrated how such data might be used in fisheries resource inventory and management. The methods used above closely approximate what is called suitability analysis. In suitability analysis, a database is assumed to exist and to contain information relevant to some set of research questions or management decisions. The database can then be spatially queried to establish the area or areas "most suitable" for some development or action. For example, in the above case, with more information, we might have produced images showing the most suitable areas for shrimping closures or for the use of FEDs (areas vital to the shrimp industry that are also productive nursery grounds). Later exercises will explore suitability analysis more thoroughly.

Special thanks to Gail McGarry, Research Administrator, Division of Marine Resources, Florida Marine Research Institute, Florida Department of Natural Resources. Ms. McGarry provided not only the data for this exercise but several guiding conversations concerning her work with GIS at the Florida Marine Research Institute.

References

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Exercise 2: Mapping Seagrass Using Remotely Sensed Imagery

In the previous exercise we demonstrated the importance of considering seagrass in fisheries management because of the high biological productivity of seagrass environments. In this exercise we will consider these environments once again. However, here the presence of seagrass will be seen as an indicator of the health of the wider marine environment. In addition, unlike the previous exercise that concentrated on the review of basic GIS techniques, this exercise will focus on basic image processing procedures relevant to the coastal zone.

Seagrass areas are very sensitive to pollution, particularly pollutants that affect water clarity such as sewage effluent. In the case of Boston Harbor, Massachusetts, seagrass beds have been decimated by years of industrial and sewage pollution. However, there is now an effort to clean the harbor through improved water treatment facilities. It is hoped that the quality of water in the harbor will noticeably improve in the coming years. One way to gauge the degree to which water quality is improving is by documenting the regeneration of seagrass beds.

In this exercise we will explore a methodology for mapping the extent of seagrass in Nahant Harbor, part of the greater Boston Harbor area in Massachusetts. We will use three bands of remotely sensed video imagery. These images were gathered from a video imaging system mounted aboard a small aircraft.

This method of acquiring remotely sensed data is relatively quick and inexpensive. The video product is also better suited to image processing and GIS manipulation than conventional aerial photography. We have raster images (stills from a video tape) from the green, red, and infrared portions of the electromagnetic spectrum at a one meter spatial resolution. Using these three images and two separate techniques, we will attempt to map the extent of seagrass. In the first, we will create a composite image and use an unsupervised classification technique. In the second, we will employ Principle Components Analysis (PCA) in an effort to separate variation due to different sea-bottom types from variation due to changes in water depth.

The data we have is reflectance values. That is, the value of each pixel corresponds to the amount of the sun's energy that is reflected back to the sensor. The values range from 0 (no reflectance) to 255 (very high reflectance) for each of the three wavelengths.

a) In IDRISI Explorer, set your Project and Working folder to the folder holding the data for this exercise (e.g., \UNITAR\CZ\Data\Exer2). Then examine each of the following raster files using DISPLAY Launcher and the GreyScale palette. You can view these three images side-by-side to compare the information contained in each band.

   GREEN: A raster image from a camera fitted with a green-yellow filter (545 - 555 nm).

   RED: A raster image from a camera fitted with a red filter (644 - 656 nm).

   INFRARED: A raster image from a camera fitted with a filter in the near infrared (846 - 857 nm).

Other files provided in this exercise data set:

   SEAGRASS: A vector file map of seagrass locations in Nahant Harbor.

Each of the three bands contains unique information as well as information with a great deal in common. It should be clear in all three that the shoreline runs roughly east to west across the top of the images. Housing developments can be seen to the north of the shore and a large pier is evident in the upper right side of the images. Different information, however, will come from different places on the electromagnetic spectrum. Bands lower on the electromagnetic spectrum have shorter wavelengths that will penetrate water better than long ones; they will reflect changes in the sea bottom while long wavelengths will indicate where the edge of the water is located. Knowing this, we can expect to see more of the sea bottom in the green and red images than in the infrared image. In particular, if we examine the GREEN image again, we can see that the offshore areas are richly differentiated making it difficult to discern land from water. However, even the shortest wavelengths are eventually absorbed by water as it gets deeper, and we can see reflectance diminish as the water gets deeper. In the INFRARED image, where the longer wavelengths barely penetrate the water at all, we see a sharp contrast between land and water. There is only negligible reflectance over water in this band.

1. *What would account for the very dark area (low reflectance) next to the pier as seen in the GREEN image but not in the INFRARED?*

Part 1: Data Preparation

We will begin by masking land areas from any image processing analysis. To create a mask of land areas, we will take advantage of the way water absorbs longer wavelengths.

b) Run HISTO from the Display menu on the image INFRARED and choose all of the default values. Note how the histogram is bi-modal with most of the pixels falling at the low reflectance end of the graph. We can assume, given the above discussion (and the knowledge that coastal zone infrared imagery is characteristically bi-modal), that the large hump at the low reflectance end represents all the water pixels, while the other hump represents land pixels.

To make a Boolean mask of land and water, we estimate some threshold between the two humps of the histogram (we suggest the value 80) and reclassify the infrared image accordingly. Since we are ultimately interested in the water areas, the mask should have the value 1 in those areas and the value 0 in all land areas.

c) Run RECLASS with INFRARED as the input image. Select the user-defined classification, giving a new value of 1 to all values that range from 0 to just less than 80, and a new value of 0 to all values that range from 80 to just less than 256. Call the result LANDMASK.

2. *What would happen if we tried to do the same procedure using the GREEN band?*

Note that there are many small areas in the land portion of LANDMASK that are confused with water (they may be ponds, or wetlands). It is only the contiguous water body of the harbor with which we are concerned. To isolate this area from the small water areas, we will use the module GROUP.

d) Run GROUP from the GIS Analysis/Context Operators menu with LANDMASK as the input image and LANDMASKGROUPS as the output image. Choose to include diagonals and ignore the background value 0.

In the LANDMASKGROUPS image, each contiguous clump of like values is assigned a unique identifier. The large water area we want to analyze is group number 13.

e) Use RECLASS once again to make a land mask. This time LANDMASKGROUPS will be the input image and the output image will be WATERMASK. Assign a new value of 0 to all values ranging from 0 to just less than 13, a new value of 1 to all values ranging from 13 to just less than 14, and a new value of 0 to all values ranging from 14 to just less than 62 (the maximum group number is 61).

Now we can mask out the land on each of the three filtered bands by multiplying each by the Boolean mask WATERMASK. All values in the harbor will remain the same while those on land will become zero.

f) Run OVERLAY from the GIS Analysis/Database Query menu three times and choose to multiply (First * Second) GREEN by WATERMASK to create WATERGREEN, then RED by WATERMASK to create WATERRED, and finally INFRARED by WATERMASK to create WATERIR.

Part 2: Unsupervised Classification

We will use the information from the three images as input into the module CLUSTER for an unsupervised classification. For more information on these modules, refer to the IDRISI Help System.

g) To perform the unsupervised classification, run CLUSTER from the Image Processing/Hard Classifiers menu. Specify three bands to be processed and enter the images: WATERGREEN, WATERRED, and WATERIR. Call the output image CLUSTERS. Choose the fine classification technique and the option to drop the least significant clusters. Leave the other defaults.

The new image will have pixels values corresponding to some particular ground cover (or in this case, sea-bottom type). The clusters are ordered from highest to lowest frequency (i.e., cluster 1 has the most pixels).

Clearly, it is difficult to know what the categories represent without some ground truthing. Fortunately, we have a partial ground truth of this part of Boston Harbor. The Environmental Protection Agency has produced a map of seagrass in this region. The map has been digitized and is stored as a vector file called SEAGRASS.

h) Make the CLUSTERS image active then use Add Layer in Composer to add the vector file SEAGRASS, using the Outline Black symbol file, on top of your clustered image.

> *3. Does the unsupervised classification show us where seagrass is located? What might account for the partial categorization of seagrass?*

Part 3: Principal Components Analysis

The previous procedure has shown us that using standard classification techniques on offshore data sets will produce inaccurate results due to the complications inherent in changing water depth. As water gets deeper, the range of reflectance for any particular bottom type will change causing confusion and limiting the usefulness of classification. However, many techniques have been derived for accurately extracting bottom type information from remotely sensed data based on the assumption that "bottom-reflected radiance is approximately a linear function of the bottom reflectance and an exponential function of the water depth" (Lyzenga, 1981, p.72). Knowing this, data can be transformed by a number of algorithms (c.f. Lyzenga, 1981 and 1978) to produce indices of bottom type and water depth. These algorithms work best when multiple bands are available for shallow clear water areas, when several depth control points are known, and when sea bottom type is known for at least some part of the scene.

For this exercise, we will not directly use any of the algorithm methods (see Exercise 3 for an example of water depth calculation using a well known algorithm). Instead, based on the discussion by Khan, et. al., 1992 (see also Van Hengel and Spitzer, 1991), we will assume that Principal Components Analysis can substitute for an algorithm method used to extract bottom types. Also like Khan, et. al. we assume that "the principal variation in water reflectance in the visible wavelength bands is due to changes in water depth, while the secondary variation is due to changes in bottom reflectance" (p. 607). That is, the first component of the PCA, which always explains the most variance in a given set of bands, can be used as an index to water depth. And the second component, which explains the most variance after the first component has been removed, can be used as an index to bottom type. It is important to stress that this method also works best when the area in question is shallow clear water and when some ground truth data is available.

i) Run the module PCA. In the dialog box select the option to calculate covariances directly, specify three image bands to be processed, ask for two components to be extracted and use unstandardized variables. Enter WATERGRN for band 1, WATERRED for band 2, WATERIR for band 3, and give WATER as the prefix for the files to be produced.

PCA will produce the two components and then display a number of tables showing the sources of variation in the data set. you may print the tables if you wish or simply close the module results window. (For further explanation of these tables refer to the IDRISI Help System).

j) Examine the display of component 1, WATERCMP1.

This image has values that change in a progression from north/northwest to south/southeast suggesting changing relative water depth. However, it is clear that the area we know to be seagrass is causing some confusion.

k) Select Add Layer in Composer, adding the SEAGRASS vector overlay with the Outline White symbol file. Within this area, the trend is still from shallow to deep water, but the scale is shifted such that it appears deeper than it should.

4. Suggest reasons for the limited success in calculating relative water depth from component one.

l) Now examine component 2, WATERCMP2. This image has values that change not with water depth, but from left to right, suggesting changes in bottom type. Again, add the SEAGRASS layer using the Uniwhite symbol file.

Here the seagrass area is more uniformly represented and is clearly differentiated from the large dark area west of it which we know is at a similar depth. Researchers at the EPA have identified this area of the harbor as primarily sand. However, it is unclear if other areas in the image (mostly along the shoreline) that have the same range of values as the seagrass bed represent seagrass. Also, as the water gets deeper, it becomes more difficult to say anything about bottom type.

Summary

In this exercise, we briefly looked at some of the problems inherent to remote sensing in the coastal zone. Using the example of seagrass bed detection, we saw how changes in water depth make standard unsupervised classification procedures difficult. We then explored one of the ways researchers are trying to map sea-bottom types while accounting for changes in water depth. Using Principal Components Analysis we were able to find areas which roughly correspond to known seagrass beds. The degree of precision was low using the three bands of data we had available. However, the exercise has shown that the PCA method is an improvement over standard classification techniques.

We would like to acknowledge Dick Hordon of Flight Landata for sending us the imagery used in this exercise. Also, many thanks to Matthew Liebman of the US Environmental Protection Agency, Boston for providing the ground truth knowledge that made our interpretation of the imagery possible.

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Imagery for this exercise was contributed by Flight Landata, Box 528, Newburyport, MA 01950.

Exercise 3: Modeling Bathymetry Using Remotely Sensed Imagery

Remotely sensed imagery is proving to be a useful tool to estimate water depths in coastal zones around the world. Procedures have been developed that isolate solar reflectance due to water depth from other factors. These procedures are invaluable to coastal zone research in areas that have not been extensively surveyed or in those that are changing rapidly. Unfortunately, passive remotely sensed imagery is limited by the degree to which light can penetrate water. Even very clear water, as in this exercise, will absorb all light after it is more than 15-17 meters deep. However, many coastal zone studies, such as those examining near-shore fisheries, coastal erosion, water quality, or recreation siting, are only concerned with areas of shallow water and would benefit from easily updated bathymetric estimates.

In this exercise we will calculate bathymetry for a region on the north coast of the Dominican Republic near the village of Buen Hombre. Later in the workbook (Exercise 4) we will look at the same area but we will use another application of remote sensing—change detection.[1] These procedures (amongst many others) were used in a pilot project that was designed to assess the viability of remote sensing in coastal zone research (Stoffle and Halmo, 1991). The pilot project examined Buen Hombre's climate history, ethno-history, marine ecology, and fishing practices along with related satellite applications. The project concluded that satellite monitoring is useful for detecting even small-scale changes in the environment and, ideally, it should be integrated into a multidisciplinary model designed to explain these changes.

The pilot project gives us both the data for the study area and one of the procedures we will use to calculate bathymetry. The procedure uses an algorithm for transforming a single band of information into an index of water depth that can then be calibrated to known depths. The algorithm (Stoffle and Halmo, 1991, p.34) is one of a family of algorithms that have been used to estimate bathymetry (Lyzenga, 1985; Paredes and Spero, 1983). These algorithms are based on the fact that radiance is, to varying degrees, attenuated by the water column. The degree of attenuation (the attenuation coefficient) is a function of wavelength, sea bottom types, and water column properties. There are a variety of algorithms that attempt to isolate water attenuation (and hence depth) from other factors by using different combinations of spectral bands with ratioing techniques. These multiple band techniques depend upon large amounts of "ground" truth data and a resolution fine enough to discriminate bottom types; they also are limited by the sensitivity to attenuation of the longest of the wavelengths used.

In our case, we have a resolution that makes it difficult to discriminate sea bottom types and also little 'ground truth' knowledge as to depth or bottom type. However, we do have available the shortest of the visible wavelengths—blue, and we want to take full advantage of its water penetrating properties. For these reasons we will use a relatively simple single band algorithm which assumes a constant attenuation coefficient and requires the least amount of ancillary information. The blue band will be transformed by our algorithm into an index of relative water depth—not accounting for bottom types. It will then be calibrated to actual water depth by regression analysis.

The second procedure we will use to calculate bathymetry utilizes several bands of imagery and Principal Components Analysis (PCA). This method is analogous to a multi-band algorithm that accounts for varying attenuation coefficients for different bottom types as it calculates water depth, unlike the single band algorithm we will use (Van Hengel and Spitzer, 1991). However, while this and other algorithm methods that account for bottom type are dependent upon extensive ground truth information, the PCA method produces a depth dependent variable (independent of bottom type) without ground truth data. The first component of PCA, using the three TM bands of imagery, should approximate relative water depth given the assumption that depth explains the most variance between two or more bands of information (see Exercise 2).

However, before we do either of these procedures it is important to examine our study area. We will do this by creating a color composite from the three bands of TM data provided.

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1. Data for both exercises were made available by the Environmental Research Institute of Michigan (ERIM), Ann Arbor, Michigan, USA.

Part 1: Data Exploration

a) Using IDRISI Explorer, set your project and Working folder to the folder holding the data for this exercise (e.g., \UNITAR\CZ\Data\Exer3). Open DISPLAY Launcher and use the GreyScale palette and the default 256 autoscaling option to examine the three bands of satellite data provided for this exercise. Also, look at their documentation files in Metadata from the Files tab of IDRISI Explorer. The files are:

TM1_85	Landsat TM, 1985, visible blue.
TM2_85	Landsat TM, 1985, visible green.
TM3_85	Landsat TM, 1985, visible red.

Other data provided with this exercise include:

WATERMASK	A raster image in which water has a value of one.
DEEPAREA	A vector polygon of the known deep-water area in the imagery.
SITES	A vector point file of the locations of known depths.
DEPTHS	A values file of known depths.
LATLONG-NAD27	A geodetic coordinate system parameter file.

Part 2: Creating a Natural Color Composite

Clearly, without much knowledge of the area, it is difficult to even separate the water areas from land in the Landsat imagery. Therefore, to get a better idea of the area, we will combine information from the blue, green and red bands to produce a natural color composite image.

b) Run the module COMPOSITE from the Display menu, using TM1_85 as the blue band, TM2_85 as the green band, and TM3_85 as the red band. Specify TM85COMP as the name of the output image and choose the linear with saturation points stretch type, create a 24-bit composite with original values and stretched saturation points, and enter 2.5 as the percent to be saturated. Do not omit zeros from the calculation in stretch since any zero values in our images are actual data values.

The image that you are seeing is a natural color composite. It approximates what you would perceive with your eye. A complete description of this image would not only require skills in interpreting remote sensing data but also extensive knowledge of the area. For our purposes, it suffices to point out a few coastal features of the image. The bright white, smooth patches on the coast are sand beaches. You will also see some small white patches inland that have fuzzier boundaries. These are clouds. Some of the very dark patches on the land are shadows caused by the clouds. Just beyond the sand beaches are submerged mangroves seen as smooth dark green areas, and beyond these is the ocean, shown in various shades of blue. The lighter the shade of blue, the more shallow the water. The bright white patches in the ocean are coral reefs. Surrounding these reefs and in other parts of the ocean are green patches indicating the presence of macro-algaes and seagrass meadows.

1. *Clearly the composite image shows changes in water depth. Would it be possible to simply reclassify this image (or any of the three original images) into an index of water depth? Why not?*

While the composite image gives us a general picture of the area in question, it cannot be used as an index of water depth. The change in radiance in the composite, or in any of the three raw bands, is due not just to changes in water depth but to changes in sea bottom type, interference from wave action and atmosphere, water quality, etc. Classification of these images into categories representing depth would be impossible.

Part 3: Removing Random Noise and Striping

Before we move on to do our bathymetric analysis, we must do some minor data preparation. Both the single band algorithm and the PCA method are sensitive to random noise and striping within the raw imagery. Therefore, before we proceed we will filter our imagery with a low-pass (mean) filter.

c) Run the module FILTER from the Image Processing/Enhancement menu on each of the three bands of TM data. Specify a mean 3*3 filter and call the output images FILTM1, FILTM2, and FILTM3.

2. *How does this filter remove random noise and striping? What general effect will mean filtering have on the imagery?*

Part 4: An Algorithm for Estimating Bathymetry

We are now ready to calculate bathymetry using the single band algorithm method. The algorithm is as follows:

$$Z = \frac{-1}{2k}\ln(V - VS) + \frac{1}{2k}(\ln VO)$$

where,

Z	=	depth (in feet);
V	=	observed signal radiance;
VS	=	portion of signal resulting from scattering of radiation in the atmosphere, water column, and water surface;
k	=	water attenuation coefficient;
VO	=	sensitivity factor consisting of contributions from solar irradiance at the surface, the bottom reflectance, atmospheric transmission, and sensor equipment.

If we assume that the actual observed radiance (*V*) varies exponentially with water depth, we see in the equation that, after the portion of the signal due to scattering (*VS*) is removed, radiance is logarithmically transformed to a linear function of depth. The result (let's call it *X*) can then be put back into the equation. Given our initial assumption of a relationship between radiance and depth, the equation now takes the form of

depth = slope (*X*) + constant

The line this equation describes is the best fit of a simple linear regression using known depth measurements as the dependent variable and the transformed radiance values (*X*) as the independent variable. The slope of this line is related to the water attenuation coefficient such that

$$\text{slope} = \frac{-1}{2k}$$

and the constant value is given by

$$\text{constant} = \frac{1}{2k}(\ln VO)$$

By first calculating the transformed radiance values and then regressing them against control points of known depth, we can calculate all of the variables in the above equation and produce our estimate of bathymetry.

Transforming the Radiance Values

The transformed radiance values can be calculated by taking the values from FILTM1, subtracting *VS*, and then taking the natural log of the result. We can estimate *VS* from the spectral properties of the deepest water in our image; water that is known to be at a depth beyond the penetrating ability of even the blue band. Assuming that such deep water should have virtually zero radiance values in the blue band, any reflectance registered must be due to scattering. To estimate *VS*, then, we simply take the average value of the pixels that lie in known deep water and subtract one standard deviation.

A vector polygon file, DEEPAREA, has been provided that outlines the known deep water area we will use to estimate *VS*. We will examine deep-water reflectance values for the mean and standard deviation by extracting the radiance values of the outlined area to a new file, and doing simple statistical analysis on that file.

d) First, we must rasterize the vector polygon to use it with the raster TM image. To rasterize any polygon, we first must create an initial image to update. This is done by running the module INITIAL from the Data Entry menu. Choose to Copy spatial parameters from another image. Call the output image DEEPMASK, and enter FILTM1 as the image from which to copy parameters. Choose integer as the output data type (because the vector file DEEPAREA has integer ID type) and specify an initial value of zero.

e) Next, use the module RASTERVECTOR from the Reformat menu to update the image DEEPMASK with the vector file DEEPAREA. RASTERVECTOR will change the value of the raster image DEEPMASK from zero to one (the identifier value of the polygon) for all pixels within the polygon.

f) We can now use this Boolean mask and the module EXTRACT from the GIS Analysis/Statistics menu to find the mean and standard deviation values for the deep-water radiance values of FILTM1. Run the module EXTRACT and specify DEEPMASK as the feature definition image and FILTM1 as the image to be processed. Choose the option to calculate all listed summary types. The results are written in tabular output to the screen.

3. What is the mean (average) value of the deep areas (category 1)? What is the standard deviation? What is the estimated value of VS for our image? (Round all answers to 4 decimal places.)

g) For the next step in the equation, subtract the value of *VS* from FILTM1. Use the SCALAR module from the GIS Analysis/Mathematical Operators menu. FILTM1 is the input image, specify FILTM1-VS as the output image name, enter the scalar value for VS found above and choose the subtraction option.[2] You may find it helpful to change the palette for the display to GreyScale.

Next we want to transform the values in FILTM1-VS to their natural logarithms. However, there are many negative and zero values in the image FILTM1-VS—numbers whose natural log makes no sense (you can observe this using HISTO in Display.) Fortunately, we can assume that all of these numbers fall in the deepest water category. Therefore, we will reclassify all those values in the image FILTM1-VS that are below one to equal one before we find their natural logs (we choose the value one because the result of reclassification has to be an integer).

h) Run RECLASS from the GIS Analysis/Database Query menu. Use FILTM1-VS as the input image, call the resultant image RECLFILTM1, and specify that all values in the range -999 to just less than 1 be reclassified to 1. Click OK. All other values will remain as before, but rounded to the nearest integer.

i) Finally, use the module TRANSFORM from the GIS Analysis/Mathematical Operators menu to convert the values in RECLFILTM1 to their natural logarithms. Call the transformed image TRANSTM1.

Display FILTM1 and then TRANSTM1 with the GreyScale palette. The difference between the original image and the

2. Note that Image Calculator may also be used to perform all the operations offered by the modules SCALAR and TRANSFORM and some of the functions of OVERLAY.

transformed image is striking.

> 4. *Describe the difference between FILTM1 and TRANTM1 for the offshore areas. What can you see in TRANTM1 that you could not in FILTM1?*

Regression Against Known Depths

Now that the data has been transformed, we can run a linear regression of the transformed data against known depths. There are 13 locations scattered across our TM imagery where depth is known. This data was collected in the field using sounding equipment and a Global Positioning System (GPS) receiver and is currently in a geodetic coordinate system. However, our TM imagery is referenced to the UTM coordinate system. Before the regression can be performed, we must re-project the depth sites to UTM coordinates. After re-projecting, we will rasterize the site locations, and then use the rasterized sites to extract the transformed radiance values to a values file. Finally using this newly created values file and a given values file of known depths, we will run a regression.

j) View the metadata for SITES, a vector file of known depth locations, and any one of the image files. Note the different reference systems. We will use the module PROJECT, as in Exercise 1, to transform the SITES coordinate system from LATLONG-NAD27 to UTM19N-NAD27. A reference system parameter file for LATLONG-NAD27 is provided in the exercise data, while UTM-19N can be found in the Georef folder.[3]

k) Run PROJECT and specify a vector file type. Enter SITES as the input file, SITESUTM as the output file, and UTM-19N as the output reference system parameter file. To see where the re-projected points are located, use DISPLAY Launcher to view TRANSTM1 with the GreyScale palette and select Add Layer to overlay SITESUTM with the Outline White Symbol file.

l) To extract the data in TRANSTM1 at the known depth sites, we will first rasterize SITESUTM onto a new image. Run INITIAL to create a new image called FEATURE. Specify byte format, an initial value of zero, and copy the spatial parameters from TRANSTM1.

m) Run the module RASTERVECTOR using SITESUTM as the vector point file and FEATURE as the file to be updated. Choose to record the identifiers of the points.

The file FEATURE now has a value (other than zero) at each pixel that corresponds to a point location, and it can be used to extract the transformed radiance values in TRANSTM1 at the same locations.

n) Run the module EXTRACT. Specify FEATURE as the feature definition file, TRANSTM1 as the image file to be processed, choose to output a values file of minimum values and call the result TRANSTM1. (Note that because a values file has a different extension, it can have the same name as the original image file.)

o) The final step is to actually run a linear regression between the values file TRANSTM1 and the file of known depth measurements, DEPTHS, which has been provided. Open one of the values files with Edit. Move that window to the side and use Edit again to open the other values file, TRANSTM1. Compare the two. Note that the TRANSTM1 file includes a value for 0, the non-site areas. This must be removed before running the regression. Delete the first line of TRANSTM1 then save the file.

p) Now run REGRESS from the GIS Analysis/Statistics menu and choose to run a regression between two attribute values files. Specify TRANSTM1 as the independent variable and DEPTHS as the dependent variable.

> 5. *Write down the resultant slope, constant value, and correlation coefficient. What is the value of k, the water attenuation*

3. To examine the details of these files, use Metadata in IDRISI Explorer while viewing reference files (.ref). For a complete discussion of georeferencing and reference system parameter files, see the Georeferencing chapter in the IDRISI Manual.

coefficient? What is the value of VO, the sensitivity factor? (To find these, solve the slope and constant equations given above for k and VO respectively.) To calculate depth by this method, do we need to know k and VO? Why not?

Calibrating to Known Depths

The above procedures have given us all the information needed to calibrate the transformed radiance values to water depth using the original algorithm. However, rather than plugging in the values of *k* and *VO*, we can directly use the slope and constant values produced during the regression analysis to save a few steps. The new form of the equation is

Depth = Constant + (Slope * [TRANSTM1])

q) To solve it, we could use SCALAR twice, but will instead use Image Calculator to save a step. Open Image Calculator from the GIS Analysis/Mathematical Operators menu or from its toolbar icon. Enter the equation as above in the Expression to process input box except enter the output filename DEPTH-ALG (for depth using the algorithm method—we will be creating another depth image later and will need to distinguish between the two). Use the values you found for Slope and Constant. Note that to enter an existing image in Image Calculator, you can click on the Insert Image button, choose the image from the pick list and it automatically inserts square brackets around the filename. Finally click the Process Expression button.

6. *Does DEPTH-ALG look like a map of water depths? What might we do to make the image more "readable?"*

7. *Fill in the following table by extracting the estimated values for depth from DEPTH-ALG (using FEATURE as the feature definition file, minimum as the summary type) to a values file (call it DEPTH-ALG). View the values file DEPTH-ALG as well as the file called DEPTHS using Edit and copy the values to the appropriate column. We will fill in PCA Depths later in the exercise.*

Site Number	Known Depths	Algorithm Depths	PCA Depths
		correlation coefficient *r* =	correlation coefficient *r* =
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			

13			

To give the image DEPTH-ALG a more map-like appearance, we can reclassify the depth values into discrete categories and mask the land areas which now have senseless values (depths).

r) Run RECLASS using DEPTH-ALG as the input image, specify TMPRECL as the output image, and reclassify to the following categories:

1 = -22 to just less than 5 (corresponds to 0 - 5 feet deep)

2 = 5 to just less than 10

3 = 10 to just less than 15

4 = 15 to just less than 20

5 = 20 to just less than 25

6 = 25 to just less than 30

7 = 30 to just less than 999 (any number over 30)

s) Next run OVERLAY with TMPRECL and WATERMASK using the multiply option. This will force land areas to have a value of zero. Call the result DEPTH-ALG-FINAL because it is our final map of bathymetry using the algorithm method. The image should be viewed using a qualitative palette.

Part 5: Using PCA to Estimate Bathymetry

This next section will demonstrate the second method we will use to estimate bathymetry, Principal Components Analysis (PCA). The input images into the PCA will be the TM imagery transformed, just as in the algorithm method. While the algorithm method assumes that the transformed blue band corresponds directly to water depth, PCA will assume that the first component from an analysis using all three bands (transformed) will correspond to water depth. It is the first component result that then can be calibrated to known water depths in the same manner as above.

Transforming the Radiance Values for Bands 2 and 3

Using the same method we used in the previous section to transform Band 1 we will now transform TM bands 2 and 3. Recall that we began by finding the value for signal due to scatter (*VS*) from the mean and standard deviation of the known deep water area in the blue band. We then subtracted *VS* from the observed signal radiance (*V*) and found the natural log of the difference. The result was the transformed image TRANSTM1 which was then used as the input into our depth equation. To perform our PCA, we need to produce TRANSTM2 and TRANSTM3 as well.

t) Repeat the exact steps from the paragraph above for each of the remaining bands. Begin by finding *VS* for FILTM2 and then for FILTM3. Note that it is not necessary to repeat the steps to create DEEPMASK as this image already exists.

8. What is the mean value of the deep water area in FILTM2? FILTM3? What are the standard deviations? What is the estimated value of VS for each image?

u) Knowing *VS* for each band, proceed to find TRANSTM2 and TRANSTM3.

Because the PCA module requires that input files be of a byte/binary format, we will have to stretch TRANSTM1, 2, and 3 to a value range of 0 - 255. Then, to make our analysis more accurate, we will mask the land areas for all three stretched images and use the results as the input files for the PCA module.

v) Run the module STRETCH from the Image Processing/Enhancement menu on each of the transformed radiance images. For each, choose a linear contrast stretch, do NOT leave out zero values, enter a lower bound of 0 and an upper bound of 6 and specify that the image is to be stretched to 256 levels. (The lower and upper bounds are chosen as a range within which all three bands' values fall.) Call the results STRTM1, STRTM2, and STRTM3.

w) We will now mask each of these stretched images by using the module OVERLAY. Run OVERLAY and multiply each of the stretched images by the file WATERMASK. Call the results MASKTM1, MASKTM2, and MASKTM3. These images will be the input files for our PCA.

Running PCA with the Transformed Data

x) Using the module PCA from the Image Processing/Transformation menu, calculate covariances directly and indicate that 3 files will be used. Enter the filenames MASKTM1, MASKTM2, and MASKTM3. Choose to extract 1 component, and give PCA as the prefix. Finally, choose to use unstandardized variables. PCA will produce the first component and then display a number of tables showing the sources of variation in the data set. Display the resultant file, PCACMP1. This is the first component, and as such it should explain the most variance in our data set. We assume that change in depth explains the most variance and that other factors, such as a changing bottom type, will be secondary sources of variation. These secondary sources of variation may show up in subsequent components (see Exercise 2).

Regression and Calibration to Known Depths

The file PCACMP1 now can be calibrated with known depths in the same manner TRANSTM1 was calibrated in the previous section. You will recall that after re-projecting the locations of known depth sites, we extracted to a values file the transformed image values at the known site locations. We then ran a regression using this values file and the file of known depths. Knowing the slope and constant values from the regression, it was easy to calibrate the transformed data to depth. We will simply repeat this procedure with PCACMP1 instead of TRANSTM1.

y) Run the module EXTRACT and specify FEATURE as the feature definition file, PCACMP1 as the image file to process, choose to output to a values file, select the minimum summary option, and call the values file PCACMP1.

z) Before running the regression, it is necessary to remove the extracted value for the background. Open the values file PCACMP1 with Edit and remove the first line. Save the file. Now run REGRESS from the GIS Analysis/Statistics menu using the values file PCACMP1 as the independent variable and DEPTHS as the dependent variable.

9. What is the resultant slope, constant, and correlation coefficient (r)? Write these down.

aa) As in step q, calibrate PCACMP1 to known depths using Image Calculator with the values you found for constant and slope in the expression. Call the output image DEPTH-PCA. You may find it useful to change the palette for the output display to be GreyScale.

ab) Extract the estimated depths in DEPTH-PCA for the known sites (FEATURE) to create a values file DEPTH-PCA using the minimum summary option. Open the file in Edit and finish the table of estimated depth values above.

10. Is DEPTH-PCA a better estimation of depth than DEPTH-ALG? How can we tell?

To better compare the results of our PCA to the algorithm method, we can reclassify and mask DEPTH-PCA in the same way we did DEPTH-ALG when we produced the map of bathymetry, DEPTH-ALG-FINAL.

ac) Run RECLASS with DEPTH-PCA as the input image, TMPRECL as the output image, and reclassify to the following categories:

1 = -20 to 5 (corresponds to 0 - 5 feet deep)

2 = 5 to 10

3 = 10 to 15

4 = 15 to 20

5 = 20 to 25

6 = 25 to 30

7 = 30 to 999 (any number over 30)

ad) Again, use this temporary file (TMPRECL) and WATERMASK file in OVERLAY to make the land areas equal to a value of zero. Call the result DEPTH-PCA-FINAL--our final map of bathymetry using the PCA method. Compare DEPTH-PCA-FINAL to DEPTH-ALG-FINAL.

ae) Optional: You may at this point wish to use Symbol Workshop with the palette option to produce a custom palette for displaying these bathymetric images. See the IDRISI Help System for detailed information about the operation of Symbol Workshop.

Summary

In this exercise, we produced images of absolute bathymetry using two different but related methods. The first method used a single band algorithm and assumed a constant water attenuation coefficient throughout the blue band. To assume otherwise would have required more ground truth knowledge about bottom type than was available. When such data is available, there are a number of algorithms that might be used to effectively isolate changes in depth from changes in other factors. When it is not available, the single band method works well as a rough estimate of bathymetry as our analysis has shown.

The second method used Principal Components Analysis (PCA) in an attempt to adjust for varying water attenuation coefficients without additional ground truth data. This procedure is based on the assumption that the first component result of PCA, that which explains the most variance in the data set, will be a depth-dependent variable that is independent of other sources of variation such as bottom type. After producing the first component image and calibrating it to known depths, we compared the results to the algorithm method.

It is clear that both methods can be used as rough estimates of bathymetry and that these and similar methods might prove useful in situations where little or no ground truth information is available. However, it is vital that we look upon such estimates as only the first step toward mapping bathymetry for a given area. In any method we must be aware of the possibility for error at each of the steps involved and continually question our results. While the dynamic nature of the coast makes precision in bathymetric estimation difficult (e.g. tides, waves, lack of ground truth information), it also makes such analyses essential if we are to have recent and/or time series data for the coastal zone.

Thank you to Thomas Wagner of the Environmental Research Institute of Michigan (ERIM) for initially providing the data for this exercise. Also, many thanks to Jeffrey Michalek, also of ERIM, for several guiding conversations concerning methodology.

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Exercise 4: Coastal Change Detection in the Dominican Republic: A Remote Sensing Approach

The detection and monitoring of change in coastal regions, due to both natural and human causes, is critical to the successful management of these environments. Although traditional surveying techniques are important, they may not be practical for the regular monitoring of large areas. Remote sensing techniques offer unique capabilities for identifying change in the coastal landscape. When remote sensing techniques are used to identify areas that may be experiencing significant change, then traditional survey techniques are used to assess the condition of these areas in greater detail, an economically feasible and analytically powerful hybrid of traditional and modern methods is created.

This exercise explores the use of remotely sensed data for detecting changes in a coastal environment near the fishing and farming community of Buen Hombre on the northern coast of the Dominican Republic. This coastal environment consists of several habitats including mangrove forests, shallow water seagrasses, macroalgae, and coral reefs. The data for this exercise are images from the Landsat satellite's Thematic Mapper sensor for February 2, 1985 and January 4, 1989.[1] For this study, we will use only the three visible bands, Blue, Green, and Red, as the habitats of interest are in clear shallow water and visible light can penetrate such water. The methodology for most of the exercise follows that outlined by Stoffle and Halmo (1991) and Michalek et. al. (1993).

Part 1: Exploring the Data

There are two very important procedures that must be undertaken prior to any change analysis. First the images of the two dates must be geometrically registered so that corresponding pixels in all of the images refer to exactly the same place on the ground. Resampling or rubber sheeting is used with a set of control points to either make one image set match the other, or to make both image sets match a base map. This has already been done with our images. The 1989 set was geocorrected to match the 1985 set.

The second pre-analysis procedure involves the radiometric correction of the imagery to compensate for changes in the satellite sensor between the two dates. Satellite sensors degrade over time and we do not want those changes caused by degradation of the sensor to be interpreted as actual change on the ground. Many procedures exist to correct for offset (an overall increase or decrease in the reflectance values for a scene) and gain (a change in the range of reflectances recorded for a scene). (See, for example, Eastman and McKendry, 1991, and Michalek et. al., 1993.) Again, this radiometric correction has already been applied to our data.

We will need the following data files from the Exercise 3 data set for this exercise:

TM1_85	Visible Blue, 1985.
TM2_85	Visible Green, 1985.
TM3_85	Visible Red, 1985.
WATERMASK	Binary mask of land and water.

And the Exercise 4 data set:

TM1_89	Visible Blue, 1989.
TM2_89	Visible Green, 1989.
TM3_89	Visible Red, 1989.

You can either copy the Exercise 3 files to the Exercise 4 folder, or add Exercise 3 as a Resource folder in your Project in

1. Data for this exercise were obtained from the Environmental Research Institute of Michigan (ERIM), Ann Arbor, Michigan, USA.

IDRISI Explorer.

a) Use DISPLAY Launcher with the GreyScale palette to examine some of the images. Note that clouds obscure much of the land area in the 1989 image.

b) To get a better idea of the area, we will now combine information from the blue, green and red bands to produce a natural color composite image. Run COMPOSITE using TM1_85 as the blue band, TM2_85 as the green band, and TM3_85 as the red band. Give D85COMP as the name of the output image. Specify linear with saturation as the stretch type, choose to create a 24-bit composite with original values, and specify 2.5% as the percent to be saturated. Do not omit zeros from calculation in stretch since any zero values in our images are actual data values, not background values.

The image that you are seeing is a natural color composite. It approximates what you would perceive with your eye. A complete description of this image would not only require skills in interpreting remote sensing data but also extensive knowledge of the area. For our purposes, it suffices to point out a few coastal features of the image. The bright white, smooth patches on the coast are sand beaches. You will also see some small white patches inland that have fuzzier boundaries. These are clouds. Some of the very dark patches on the land are shadows caused by the clouds. Just beyond the sand beaches are intertidal mangroves seen as smooth dark green areas, and beyond these is the ocean, shown in various shades of blue. The lighter the shade of blue, the more shallow the water. The bright white patches in the ocean are coral reefs. Surrounding these reefs and in other parts of the ocean are green patches indicating the presence of macro-algae and seagrass meadows.

c) Now that we have a brief description of the coastal zone in 1985, repeat the process of creating a composite image for 1989 *except* use a 10% saturation on each end to compensate for the large areas covered by clouds and cloud shadows in the scene. Call the output D89COMP.

The obvious difference between the two composites is due to the large percentage of the image covered by clouds and cloud shadows in 1989. Fortunately these features are mostly confined to the land area and we are interested primarily in the shore and seaward areas. We will see later, however, that the presence of these clouds significantly complicates our change analyses.

> 1. *Do you see any noticeable changes in the coastal environment between 1985 and 1989? If you do, make a note of where these differences occur.*

Visual detection of change in the coastal environment is very difficult. Therefore, we will now explore a few techniques that will allow us to use the computer and GIS to detect and analyze change. We will examine two basic types of image comparisons. Pairwise comparisons, which make use of one image from each date, will be the focus of the first section. We will use techniques of Image Differencing and Image Ratioing with the blue visible bands to identify areas of significant change. The second type of comparison is that between a set of multiple images from one date and a corresponding set from another date. This will be explored in section 3 using all six images in the data set and the Change Vector Analysis technique. Again, the goal will be to identify areas of significant change. For a more detailed discussion of these and other concepts of change, see Eastman, McKendry, and Fulk 1991.

Part 2: Pairwise Comparisons

Image Differencing

As the name implies, Image Differencing utilizes the difference between two images to detect change. We will apply this technique using the blue bands from 1985 and 1989 since this band is best able to penetrate the clear and shallow waters of the ocean.

d) Use the OVERLAY module and the Subtract option to find the difference between TM1_89 (first image) and TM1_85 (second image) and call the output image DIFF. In this image, very dark blue to black pixels represent large negative change (reflectance decreasing from 1985 to 1989) while bright green pixels represent large positive change (reflectance increasing from 1985 to 1989). Use Cursor Inquiry Mode to examine a few values and to determine which color includes zero change values. You may also want to add the DIFF image onto the D89COMP image to further visualize the result. With D89COMP displayed, use the Add Layer option from Composer to add the raster image DIFF. Then toggle DIFF on and off by clicking its checkmark in Composer.

2. *What is the most noticeable change event shown in this image? Can it really be referred to as "change"?*

As it exists now, DIFF is not very useful since it does not provide any information about whether the change that is recorded is or is not significant. That is, it does not indicate whether the change is due to normal variation or whether it is true change. In effect, we need to establish threshold values beyond which we expect to find true change areas.

If we had good knowledge of the study area or were able to go into the field to collect some ground truthing information, we would be able to identify areas that we know have undergone significant change and areas that have not. We could examine the values of DIFF for these areas and use these values as the basis for determining a threshold value for the entire study area that we feel identifies significant change areas. In the absence of such knowledge or opportunity, we will rely on a different, more arbitrary method for determining the threshold value.

One way to determine threshold values is to assume that the distribution of values in DIFF is Normal or Gaussian in shape. In this case, we may use the mean and the standard deviation of the image to set threshold values. In a normal distribution, 90% of the values in the image will fall within 1 standard deviation of the mean, 95% within 2 standard deviations of the mean, and 99.5% within 3 standard deviations of the mean (if you are not sure what these terms mean, refer to any standard text book on statistics). We may arbitrarily decide that any change falling within plus or minus two standard deviations of the mean (95% of all values) is really just normal variation and should not be considered as significant change. Following this logic, we will consider the 5% of pixels that fall outside this interval to represent true change. We will use this technique to threshold DIFF.

e) Use HISTO with the image DIFF. Enter a class width of 1 and choose a graphic output. A frequency histogram of DIFF will display on the screen.

3. *What do you think causes the small peak at the right end of the histogram?*

4. *What are the minimum, maximum, mean and standard deviation values of the image? (Round values to two decimal places.)*

Clearly the presence of clouds in the 1989 image is making the difference image bimodal, and hence our assumptions about a normal distribution are not very accurate. We will go ahead and threshold the image, however, as if it did have a normal distribution. Afterwards we will attempt to remove the cloud effects from the analysis and we will compare the two results.

To create the threshold image, we will use the RECLASS module and the mean and standard deviation information found above. Calculate the following values:

Mean minus two standard deviations.

Mean plus two standard deviations.

f) Use RECLASS and the above values to reclassify DIFF such that:

Assign a new value of 1 for values from the minimum to the mean minus 2 standard deviations.

Assign a new value of 0 for values from the mean minus 2 standard deviations to the mean plus 2 standard deviations.

Assign a new value of 2 for values from the mean plus 2 standard deviations to the maximum.

Call your output image CHANGE1.

5. *What values did you use for the reclassification?*

6. *Where are the areas of greatest positive and negative change? Where are they if we try to ignore the effects of clouds and cloud shadows?*

It is known that the water level in 1989 was significantly deeper than in the 1985 image due to tidal change. This causes the shallow coastal areas in the 1989 image to appear darker than in the 1985 image. This, combined with the darkening effects of cloud shadows, make it impossible to confidently point to areas of significant negative change in the coastal region. All negative change in this data set will, therefore, be considered ephemeral and we will only concentrate on finding significant positive change.

The large presence of positive change areas, attributable to clouds in 1989, obscures other areas of significant positive change. In addition, the presence of those very high positive change values associated with clouds caused the mean of DIFF to be high in relation to the non-cloud image and the standard deviation to be larger than would be if no clouds were present (the effect is not balanced by the negative effects of shadows and deep water because clouds appear solid white while their shadows and deep water are very dark). We will now attempt to "mask out" the cloud areas and create a new significant change image. We want to mask out just clouds and not cloud shadows as well because if there is a strong positive change in a shaded area it may still appear in the analysis.

Making a mask image for only the clouds is problematic because very bright values are found in the beach and coral reef areas as well as in the clouds. This frustrates attempts to use RECLASS to isolate clouds. These areas are bright in all three bands, making it difficult to use classification techniques to distinguish clouds from sand and coral as well. Since we are interested in change only in the beach and seaward areas and not on land, and since most of the clouds appear over the land area, we may partially solve the problem by simply masking out the entire land area. A mask image is provided in your data set with the name WATERMASK.

g) Display WATERMASK with the Qualitative palette. Note that the value of the water, beach and mangrove areas of the image is one and the value of the non-beach land areas is zero.

h) Use OVERLAY to multiply WATERMASK and DIFF and call the resulting image DIFFMASK.

Note that some of the cloud effects still remain. Through onscreen digitizing in IDRISI, we can further remove these effects. Another mask image is provided that is free of land, clouds and shadows.

i) Display CLOUDWATERMASK with the Qualitative palette. Note that this image is similar to the WATERMASK image except for further removal of clouds.

j) Now we are ready to use the new mask image to mask out all the areas from our difference image that are of no interest. Run OVERLAY to multiply CLOUDWATERMASK and DIFF to create the output image DIFFMASK. We will want to overwrite the previous DIFFMASK which had the cloud effect still remaining.

Now that we have the final difference image with the cloud effects removed, we need to find the mean and the standard deviation and create a thresholded change image as before. Just as the high values due to clouds affected the calculation of the mean and standard deviation before when we used HISTO with DIFF, the large number of zero values present in DIFFMASK will cause the mean to be closer to zero and the standard deviation to be smaller than if the non-masked areas were considered separately. We do not want to eliminate all the zero pixels of DIFFMASK from the calculation because some of them may be actual difference values and not the result of the masking operation. What we want to do is calculate the mean and standard deviation of only those values in DIFF that correspond to pixels with the value one in CLOUDWATERMASK. We want to ignore all the values of DIFF that correspond to pixels with the value zero in CLOUDWATERMASK. The module EXTRACT will allow us to find the true mean and standard deviation for the nonzero areas.

k) Run EXTRACT and give CLOUDWATERMASK as the feature definition image and DIFFMASK as the image to be processed. Use the option to calculate all summary types.

> 7. *What are the maximum, minimum, mean and standard deviation values of category 1 of DIFFMASK? Do the changes between these statistics and those recorded in question 4 lead you to believe that the cloud effects have been adequately removed? What procedure could you use to see if the small peak of cloud values is still present in the image?*

l) Now use the mean and standard deviation you found above and the masked difference image, DIFFMASK, to create a new thresholded change image following the same procedure you used to create CHANGE1. Call the resulting image CHANGE2.

> 8. *What values did you use in the reclassification? Describe the major differences you see between CHANGE1 and CHANGE2.*

Finally, we have isolated what we believe are change areas, but we have not yet attempted to interpret these changes. Because we cannot comment on the negative changes (they may be significant or they may be due to cloud shadow or tidal differences), we will only discuss the positive changes. The original researchers who analyzed change using this data set were most interested in uncovering areas that were significantly brighter over time because bright areas are an indicator of environmental degradation while darker areas most likely signify a healthy environment. In general, the loss of macro-algae and seagrasses in an area leads to a higher reflectance in the blue band because the sand on the bottom of the ocean reflects more than the vegetation which previously covered it. Also, an increase in the brightness of coral reefs occurs when they die. Overfishing, pollution, and sedimentation can all lead to the degradation of seagrass and coral environments. Positive change is a clear indicator of such degradation.

Part 3: Image Ratioing

Although Image Differencing is useful for detecting change, it treats change in an absolute rather than in a relative sense. For example, a change in pixel values from 10 to 5 will be recorded as a change of -5 using Image Differencing. A change from 100 to 95 will also be recorded as -5. But the former may well indicate a doubling of some habitat type such as seagrasses in the water, whereas the second change may be a fairly minor change in an already substantial level of seagrasses. We may want to make our change area determinations based on the relative change in reflectance rather than the absolute difference.

To accomplish this, Image Ratioing may be used. As the name implies, with this technique, one image is divided by the other and the resulting image is then thresholded. Image Ratioing may be undertaken using the OVERLAY module. We will divide the 1989 image by the 1985 image.

m) Before carrying out this operation, use Metadata with TM1_85 to check that the minimum data value is not zero. (Division by zero can pose a problem.)[2]

n) Run OVERLAY to divide TM1_89 by TM1_85. Call the output image RATIO. Use Cursor Inquiry Mode to examine some of the values, then use HISTO, specifying a class width of 0.1, to examine the distribution of values in the image RATIO.

The scale of RATIO is not very useful. The value 1 indicates no change from 1985 to 1989, the value 2 indicates double the reflectance in 1989 than in 1985, and the value 0.5 indicates double the reflectance in 1985 than in 1989. These latter two values that seem to be opposite are not the same distance from the no-change value of one. In other words, the scale is not symmetric. To correct this problem, we will use the module TRANSFORM to convert the ratio scale to a log ratio

2. IDRISI accommodates division by zero in the following way: 0/0 = 1, positive number/0 = very large positive number, negative number/0 = very large negative number.

scale.

o) Run the module TRANSFORM and select the natural logarithm option. Specify RATIO as the input image and LOGRATIO as the output image. Now use HISTO with a class width of 0.01 to see the change in the distribution of values brought about through the natural log transformation. (Note that the small peak representing cloud areas appears in this histogram. We will exclude the cloud and land areas when we calculate the change statistics.)

Next we must create a thresholded change image from LOGRATIO to distinguish normal variation from significant change.

p) Follow the same procedure to create CHANGE3 as you did above in making CHANGE2. Use EXTRACT with CLOUDWATERMASK (feature definition image) and LOGRATIO (image to analyze) to find the mean and standard deviation. (Because of the small values, round the numbers to 4 decimal places.) Calculate the values to use, then run RECLASS.

Assign the new value of 1 for values from the minimum to the mean minus 2 standard deviations.

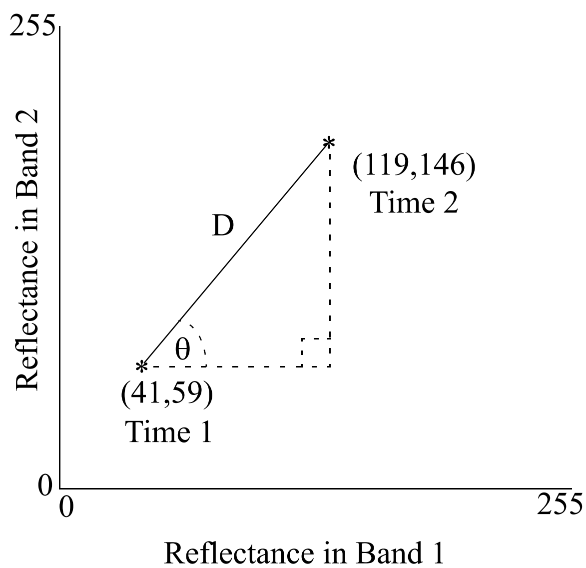
Assign the new value of 0 for values from the mean minus 2 standard deviations to the mean plus 2 standard deviations.

Assign the new value of 2 for values from the mean plus 2 standard deviations to the maximum.

Call your output image CHANGE3.

q) As a final step, OVERLAY your thresholded image with CLOUDWATERMASK to change all the land and cloud areas to the value zero. Call the result CHANGE3MASK. Change the palette to QUAL256, if necessary.

9. *What are the areas of significant change delineated in CHANGE3MASK? Do they differ from those determined by the Image Differencing technique and shown in CHANGE2?*



As we can see in the figure above, the distance between the pixel's two positions, D, can be calculated using the formula for finding Euclidean distance:

$$D = \sqrt{(X_2 - X_1)^2 + (Y_2 - Y_1)^2}$$

$$D = \sqrt{(119 - 41)^2 + (146 - 59)^2} = 116.85$$

And the direction of the change in position, the angle theta, may be found using trigonometry as follows:

$$\theta = \arctan\frac{Y_2 - Y_1}{X_2 - X_1} \quad \theta = \arctan\frac{146 - 59}{119 - 41} = \arctan 1.115 = 48.12°$$

Now let's relate these equations to this exercise. While the above example used the values of one pixel in two bands on two dates, we want to use entire images for three bands for two dates. The Euclidean distance formula given above may be extended to any number of bands. In this exercise, we are working with three bands and will therefore find the change distance using this formula:

$$D = \sqrt{(TM189 - TM185)^2 + (TM289 - TM285)^2 + (TM389 - TM385)^2}$$

The change distance image we create using this formula can then be thresholded to produce images that show only what we believe to be significant change areas.

The precise direction of change becomes difficult to determine with three bands because this moves us from two to three dimensions and requires the use of spherical coordinate geometry. For this exercise, we will determine only the change direction category to which each pixel belongs, and not its precise angular change direction. The categories will be defined by whether change was positive or negative in each of the three bands. This will produce a maximum of eight change direction categories as follows:

Change in Band 1	Change in Band 2	Change in Band 3
Positive	Positive	Positive
Positive	Positive	Negative
Positive	Negative	Positive
Positive	Negative	Negative
Negative	Negative	Positive
Negative	Positive	Negative
Negative	Positive	Positive
Negative	Negative	Negative

This change direction category information, together with our significant change distance area image will allow us to produce images showing only significant change areas that belong to the change direction categories that are of interest to our study.

Creating the Change Distance Image

We will create the change distance image following the formula given above. As you can see, there is nothing very complicated about the formula -- it is simply a collection of subtraction, addition, square and square root operations. All of these can be accomplished with the modules OVERLAY and SCALAR or TRANSFORM. Rather than run all the modules separately or write the separate commands into a macro, we will use Image Calculator.

r) Open Image Calculator. Click in the output filename box and enter the filename CHANGEDIST. Then click into the Expression to process input box and enter the following expression. Note that the Insert Image button allows you to choose image names from the pick list and automatically encloses them with square brackets.

sqrt(sqr([tm1_89]-[tm1_85])+sqr([tm2_89]-[tm2_85])+sqr([tm3_89]-[tm3_85]))

Process the expression.

s) Use OVERLAY to multiply CHANGEDIST and CLOUDWATERMASK to turn the cloud and land areas to zero. Call this image CHANGEDISTMASK. Note that all the values in the image are positive—these are euclidean distance values and give no indication of the direction of change.

t) Then use HISTO with CHANGEDISTMASK, specifying a class width of 1 and a display minimum of 0.1. This will exclude the masked areas from the histogram.

10. Is the distribution of values Normal (i.e., Gaussian)? Why not?

Because the distribution is not normal, we cannot use with this image the same thresholding technique we used before. Before, we assumed that any change beyond two standard deviations of the mean probably represents true change, while those within two standard deviations probably represent normal variation. The percentage of the values that fall outside two standard deviations on the normal curve is approximately 5%. We will use that figure to threshold this non-normal image.

HISTO may be used to generate a numeric histogram as well as a graph. The numeric histogram lists the class and cumulative frequency and could therefore help us to find the threshold value in CHANGEDISTMASK that separates 95% of the change values from the 5% of the highest values. However, HISTO includes the masked area in the calculation. If we choose 5% of the entire image area, including the masked land and cloud areas, we will be choosing considerably more pixels than we want. (Recall that the statistics we used in creating the earlier change images were based on EXTRACT results that ignored the masked areas.) We could use arithmetic to calculate what percentage of the entire image represents 5% of the unmasked areas. However, IDRISI provides a utility that will make this determination much simpler. The module QUERY extracts only the values indicated in a mask image to a new file.

u) Use the module QUERY from the GIS Analysis/Database Query menu. Specify CHANGEDISTMASK as the input image and CLOUDWATERMASK as the mask image. Choose Binary output type and give DISTQUERY as the output filename.

v) Then run HISTO with DISTQUERY. Choose the numeric display option and enter a class width of 1. Scroll down through the tabular histogram, keeping an eye on the Cumulative Proportion. When the Cumulative Proportion is 0.95, that means that 95% of the values fall at or below the upper limit given for that class. We will use this figure for our threshold value.

11. Five percent of the values in the image are above what value?

w) Run RECLASS with the threshold value you just found with CHANGEDISTMASK to create CHANGEDIST2 such that significant change areas have the value one and non-significant change areas have the value zero.

12. *Describe where the significant change areas are located. How does this image differ from those produced using pairwise comparison techniques of differencing and ratioing?*

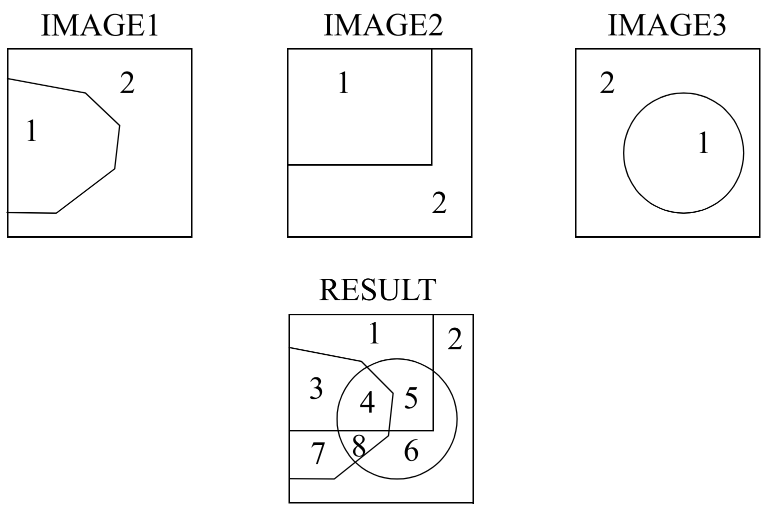
Producing the Change Direction Category Image

Now we will produce the change direction category image. As stated above, these categories are based on whether there was a positive or negative change in each of the three bands from 1985 to 1989. The first step, then, is to create an image for each band in which all the positive change values have been reclassed to one value and all the negative change values have been reclassed to another value. Following the methods of Stoffle and Halmo (1993), we will include zero change in the positive change category.

x) Run OVERLAY with the subtraction option (or use Image Calculator, if you prefer) to create these difference images among the three bands of 1985 and 1989 (e.g., TM1_85-TM1_89, TM2_85-TM2_89, and TM3_85-TM3_89). Call the difference images DIFFB1, DIFFB2, and DIFFB3 respectively.

y) Next, use RECLASS with the difference images to create 3 new images in which negative change areas have the value 1 and positive change (including 0) areas have the value 2. Call the resulting images RECL1, RECL2, and RECL3 respectively. Then use OVERLAY to multiply these images by CLOUDWATERMASK to force the areas that are not being considered to have the value 0. Call these three resulting images PNM1, PNM2, and PNM3, for Positive/Negative/Masked change in band 1, band 2 and band 3 respectively.

The next step is to find the combinations of positive and negative change in the three bands that exist for the scene. These combinations are our change direction categories. Refer to the following figure to help visualize the final image we must create. Note that each of the three input images has two values and that the result image shows the eight combinations of these classes:



The module that finds the combinations of classes is called CROSSTAB.

z) Run the module CROSSTAB with PNM1 and PNM2 and choose to produce a cross-classification image. Call the output CROSS1. Note that the order of the filenames in the title of the displayed result is the same as the order of the classes from those filenames that appears in the legend category for each class in CROSS1. For example, if the title states PNM1:PNM2, then the caption reading 3:2:1 means that category 3 in the new image, CROSS1, is where category 2 of PNM1 coincides with category 1 of PNM2.

13.   Why is there only one category that has combinations with category 0 of either map?

aa) Next, use CROSSTAB again, but this time specify the input images as CROSS1 and PNM3. Call your output image CHANGEDIR.

14.   For each category of CHANGEDIR, fill in the following table to indicate whether the changes in blue, green and red were positive, negative or masked. Recall that in all three images negative change was assigned the value 1 and positive change the value 2. HINT: Write out the combinations from CROSS1 and substitute these combinations for the first classes in CHANGEDIR. For example, category 6 in CHANGEDIR represents category 2 from CROSS1 cross-tabulated with category 2 from PNM3 (or the red band). Therefore, in category 6 we have negative change from PNM1 (blue), negative change from PNM2 (green), and positive change from PNM3 (red).

	B	G	R
1.00	mask	mask	mask
2.00			
3.00			
4.00			
5.00			
6.00	-	-	+
7.00			
8.00			
9.00			

Of particular interest to this study are the change direction categories that represent positive change in all three bands or positive change in the blue and green band but negative change in the red band. This is because corals, algae, and sea-grasses that may have been damaged or destroyed between 1985 and 1989 should change from dark to light in all three bands, or only in bands 1 and 2 since band 3 has a reduced ability to penetrate water. Also, intertidal mangroves that have been cut should also be identified using these change direction categories.

15.   What categories in CHANGEDIR represent these areas? Which change direction categories coincide with the significant change distance areas? What steps did you use to answer this last question?

Summary

This exercise demonstrated the use of four techniques for detecting change in coastal environments. Although the areas of significant change that were detected were relatively small, the usefulness of the techniques was demonstrated. The necessary link with ground truthing and field work should have become apparent as we moved through the exercise. Without a sense of what "significant change" actually means on the ground, our final change images are not very useful. In addition, the presence of ephemeral change areas, such as those due to clouds and cloud shadows was addressed. If nothing else, this aspect of the exercise should underline the desirability of working with cloud-free data. There is much promise in using such techniques to identify areas for which to focus resources for field study. As remotely sensed data become more accessible to decision-makers, these techniques will undoubtedly become more common for use in change analyses.

Many thanks to Thomas Wagner and Jeff Michalek of the Environmental Research Institute of Michigan, Ann Arbor, Michigan, USA for supplying the data for this exercise as well as much advice.

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Exercise 5: Monitoring Coastal Erosion —Adelaide South Australia

Coastal erosion is a worldwide problem that demands local action. As sea levels rise and coasts recede, the need for precise and timely monitoring grows. This exercise uses data from a local beach erosion assessment project in South Australia.[1] The beach studied is located in the greater metropolitan area of Adelaide and is part of an extensively developed shoreline only 7 kilometers from the city center. Due to its proximity to the city, much of the beach's naturally protective dune system has been built over and replaced by sea walls, and seagrasses that once slowed incoming waves have been dying due to pollution. These processes have lead to increasing rates of erosion both on and offshore that leave property, infrastructure, and recreation areas more vulnerable to storm damage.

In an attempt to combat the processes of erosion along the beach, a sand replenishment program has been undertaken. The program trucks sand from nearby deposits and dumps it in particularly vulnerable locations along the beach. The main strategy is to widen the beach and rebuild dune systems in front of developed areas. It is thought that reestablishing "natural" systems will be more effective and less expensive than other forms of coastal protection.

To better understand the coastal processes of sand erosion and accumulation along the beach, detailed profile data has been collected from 1985 to 1991 and continues to be collected on an annual basis. With this data set we will, in this exercise, clearly illustrate where sand is eroding and accumulating. We will highlight areas that are most rapidly changing, calculate the volumes of sand that are shifting, and make suggestions concerning the quantity and location of sand replenishment projects.

The data consists of four surveys (1985, 89, 90, and 91) of beach elevation and offshore bathymetry for a five kilometer stretch of beach. Each survey contains profiles of continuous elevation/bathymetry point data that run perpendicular to the beach (this point data has been converted to IDRISI raster format for this exercise). The profiles are 50 meters apart and stretch offshore to a distance of 1000 meters. This data was collected by manually measuring elevations onshore and in shallow water and by depth sensor systems in boats offshore. While there are other more automated ways to gather bathymetry data (see Exercise 3), this method provides the most accurate and detailed measurements (several thousand data points with an estimated error of only +/- 10 cm were collected). If this type of data is collected regularly, it will, over time, prove invaluable to the assessment of shoreline change.

Other data includes a vector line file representing the coastline, local roads, rivers, and the locations of sand dumps in 1989-90. Each line type is coded separately and will be used to put the elevation data in context. There is also another image file provided that is a simple binary mask of the study area and four intermediate answer images.

Part 1: Examining the Data Profiles

To start the exercise, we will examine the data sets provided. The elevation data is stored in raster format and the units are centimeters. Because zero is a possible elevation value, the background value for the images is -1500. This is well below the lowest elevation value in any of the four years.

a) Set your Working folder to that which holds the data for this exercise (e.g., \UNITAR\CZ\Data\Exer5). Use DISPLAY Launcher to examine the four elevation images ELEV85, ELEV89, ELEV90, and ELEV91 with the default Quantitative palette. Use Cursor Inquiry Mode to explore the data values and to discern the background color for each image.

1. *Remembering that these images were created from point data, where was the greatest density of data points? What do the horizontal lines perpendicular to the shore represent?*

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1. The data for this exercise was provided by the GIS section of the Department of Environment and Planning, Adelaide, South Australia.

b) Now, examine the vector data provided. Use DISPLAY Launcher, selecting the Vector file option, to view the vector file LINES. Use the default Qualitative symbol file and select to display the legend.

c) It is also instructive to view LINES on top of one of the image files. Display ELEV85 and choose Add Layer in Composer to add the vector file LINES with the Outline White symbol file.

d) Finally, examine the profile data sets using HISTO. Reset the minimum value of the histogram to be -1400 in each case. This will prevent the background value from making the histogram unreadable.

Part 2: Creating Surface Models

All steps in this exercise will require the construction of surface models from our four years of elevation/bathymetry data. Basically, this will involve the interpolation of a surface where no data exists (between the profiles). Usually, these type of models are referred to as digital elevation models (DEMs) or digital terrain models (DTMs). Because we are working with data that contains mostly negative elevations (water depth or bathymetry) we will use the former term and keep in mind that "elevation" can refer to distance below as well as above mean water level.

The elevation models can be constructed from point data (in this case rasterized) in a number of ways. The method we will use here will be to simply fill in the blank spaces of the elevation images with data equivalent to its nearest neighbor (see Exercise 1 for a different method). While this method would be inappropriate for data distributed randomly or sparsely, it works well with our regular profiles of elevation data.

In IDRISI, the allocation of data values to areas without data is a two step process. In the first step, the distance of a given cell to the nearest data value is calculated. In the second step, data values are actually allocated to the previously blank cells. However, because both of these steps use zero to represent areas of no data and the elevation data set uses -1500 to represent areas of no data, we will have to temporarily add 1500 to all cells. Then, we will use DISTANCE to calculate the distance surface from the elevation data, and ALLOCATE to fill in the now zero valued cells (the background). Because it will be tedious to run these commands four times, once for each image, we suggest that you explore using Macro Modeler, or alternatively, the IDRISI macro commands (for information on using macro commands, refer to the IDRISI Help System). For each of the following steps used to produce a surface from ELEV85, simply repeat the IDRISI command four times (in command line mode, once for each image) in a macro file. Note that you may wish to create a macro file that would run all steps or any number of other possible combinations. If you choose to do this, you can also add a DELETE command with DEL*.* as the file to be deleted, enabling you to delete all temporarily created files.

e) First run the module SCALAR to add 1500 to the elevation image ELEV85. Call the result TMPADD85.

f) Run DISTANCE from the GIS Analysis/Distance Operators menu using TMPADD85 as the feature definition file. Call the output image TMPDST85.

g) The run ALLOCATE from the GIS Analysis/Distance Operators menu using TMPDST85 as the distance image and TMPADD85 as the target image. Call the resultant surface image TMPALO85.

If you were to now examine this image, it would be clear that the allocation procedure did not stop at the boundary of our study area (the end of our profiles). Instead, zero valued cells were given data values right out to the edge of the image itself.

h) In order to clip the data back to the original size of our study area, use the module OVERLAY and multiply the TMPALO85 image with the provided binary mask called STUDYA (where 1 = the study area). Call the resultant image TMPCLP85.

i) Finally, use SCALAR on the clipped image to subtract 1500. Call this final image SURF85 and delete all of the TMP files. Repeat this procedure for each year if you chose to not use macro files. (The answer images EX5ANS1 through 4 have been provided. They are the equivalent of SURF85 through 91).

The surface images created can now be viewed in a number of ways. We suggest that you perform the following few steps on SURF91 only. However, if you feel that it is valuable, do not hesitate to look at any other year as well.

j) First, display SURF91 with the Quantitative palette and select the Add Layer option in Composer to add the LINES vector file to put the image in context.

2. What might account for the "unnatural" patterns evident just offshore in the surface images?

Another way to see the same data is by running HISTO on SURF91 and choosing the default choices. Clearly, most pixels contain the no-data value of -1500 and the bulk of the remainder is offshore water approximately 500 to 700 centimeters deep.

k) Run HISTO again and choose a minimum display value of -1400 as you did earlier with the profile data.

3. How does this histogram differ from the profile histogram? Now that the image is a full surface, what might the dip in the histogram (at approximately -300) indicate?

Another way to view the newly created surface models is to use the Fly Through module (before proceeding, please read how to use the Fly Through module in the Help System). This display allows you to see the beach in exaggerated relief. Again, we will go through the following steps for just the 1991 surface.

l) Run the Fly Through module from the Display menu. Specify SURF91 as the surface image. Do not use a drape image and keep the rest of the defaults. Once the image is displayed, use the appropriate keys to 'fly through' the image.

Part 3: Measuring Changes in Sand Volumes

The amount of sand that is being lost from the beach can be estimated by looking at the differences between the volumes of sand present in each profile year. The volume that we can measure in a given year is the amount between the surface previously created and some arbitrary base depth. This measure gives us no real indication of the actual amount of sand present; it can only tell us the volume of sand gained or lost in the study area from year to year. However, this measure of relative change from year to year tells us whether there is a net loss in sand or just local sand movement.

To calculate change in volume for the entire beach we will first transform the surface images into volume images where each cell value indicates the volume of sand in that cell in square meters.

4. How might elevation be transformed into volume? How would the new images be useful to us?

Cell volume will be the height of the cell multiplied by its length and width. Cell height will be the difference between the elevation value and an arbitrary base of 1000 cm below sea level (i.e. -1000 cm). Cell length and width are known; they are simply the cell resolution of the surface images.

m) Examine the metadata for SURF91. With that information, calculate the resolution and note the change. Because cells are square, this will be both the length and width of all cells.

n) To calculate height, run the module SCALAR to add 1000 (the equivalent of subtracting -1000) to SURF91 and call the result HTCM91, for height in centimeters (again, you may choose to do this for all four years at once using batch files or do each year separately). However, now we have height in centimeters and resolution in meters. Correcting for this is not as straightforward as it seems. To change everything to centimeters would produce unwieldy numbers and huge files in real format (remember that integer format only has a range of -32000 to 32000), while changing heights to meters means dividing by 100 (which requires that we switch the data to a real format if we don't want to lose accuracy). The best choice is the latter option where the data need only be in real format as an intermediate step and the final measure will be volume in cubic meters.

The formula for volume in cubic meters then is:

$$\left(\frac{HTCMyy}{100}cm\right)6m6m = VOLyy$$

o) Use SCALAR to divide HTCM91 by 100 and call the result HTM91 (height in meters). Run SCALAR again and choose to multiply HTM91 by 36 (the length times the width in meters). Call the result VOL91. Then repeat this process for the other three SURFyy files.

The images created represent volume by cell, whereas we are looking for changes in total volume. The EXTRACT module can calculate a number of summary statistics for a given area in an image. We will use it to find the sum (option 3) of cell volumes in the study area.

p) Run EXTRACT once for each volume image and specify STUDYA as the feature definition file. Have EXTRACT output the sum (total) as tabular output and fill in the following table. Note that we are interested in category one only, the study area category in the Boolean image STUDYA.

Total Volumes	Differences	Total Difference
1985:		
	85-89:	
1989:		
	89-90:	85-91:
1990:		
	90-91:	
1991:		

The table indicates that the beach underwent a net loss of sand from 1985 to 1989. However, the intervals since 1989 indicate increases in net sand such that the total difference across the study period is in fact slightly positive.

5. *How can we account for these measures if our initial assumption was that erosion was a major problem at this beach?*

If we take into account the fact that the sand replenishment program added approximately 300,000 cubic meters of sand to the beach between 1989 and 1990 and that the program continued in the year after as well, it is clear that the table is quite accurate. Net losses of sand across the four years previous to 1989 were replaced by trucking in sand from another site.

While the net numbers are encouraging, the data set is detailed enough to provide much more information. In particular, where along the beach is the greatest erosion and accumulation occurring? What type of impact did the sand replenishment programs have? Did they arrest erosion or merely balance the net numbers? Are there critical areas of erosion not being covered by the dump sites?

Part 4: Locating and Analyzing Critical Areas

Mapping Change

The most direct way to obtain detailed data on sand erosion and accumulation along the beach is to create images that show the difference in elevation from year to year. Areas of change can then be reclassified into levels of positive change (sand accumulation) and negative change (sand erosion). From this reclassification we can isolate areas of severe erosion and exceptional accumulation. Finally, summary statistics for these areas can be examined.

From our previous net volume analysis, it is clear that an image that shows difference in elevation from 1985 to 1991 may not capture the complexity of change. Therefore, we suggest that a difference image be created for each of the three intervals (85-89, 89-90, 90-91).

q) To create them, run the module OVERLAY and subtract the SURF images for the earlier years from the SURF images for the latter and call the results DIFF8589, DIFF8990, and DIFF9091.

This will produce images of continuous data representing changes both positive and negative that must be reclassified. However, before reclassifying, the background data value which became 0 in the difference images must be reset to -1500.

r) To do this, RECLASS the STUDYA image such that the study area equals 0 and the background area equals -1500. Call the result BACKGRND. Then OVERLAY the new mask such that it covers the difference images and call the corrected images CORR8589, CORR8990, and CORR9091.

s) All of the corrected difference images should then be reclassified to the categories listed below. Run RECLASS on each of the corrected images and call the resultant images representing discrete categories of change CHNG8589, CHNG8990, and CHNG9091. You may want to save the first RECLASS operation to an .rcl file to be used in the other reclassifications. You may also wish to adjust the legend to reflect the change categories and then display them with the user defined palette called CHANGE.

Category	Range
0.00	-1500 (background)
1.00	< -500 cm
2.00	-500 to -200 cm
3.00	-200 to -100 cm
4.00	-100 to -50 cm
5.00	-50 to -20 cm
6.00	-20 to 20 cm (no change)
7.00	20 to 50 cm
8.00	50 to 100 cm
9.00	100 to 200 cm
10.00	200 to 500 cm
11.00	> 500 cm

Visual analysis of the three images produced will reveal large amounts of information concerning the locations of erosion and accumulation. One way to compare them against each other is to display them simultaneously.

t) Run the module CONCAT from the Reformat menu to make all three change images appear side-by-side. Use CHNG8589 as the main reference image and the other two change images as the paste images. You will need to know the number of columns and rows in these images in order to paste them correctly. This information can be found in the metadata for the files. Call the concatenated image CHNGALL and view it with the CHANGE palette.

The results of sand dumping since 1989 should be obvious in the images. Because the general trend is for sand to flow north along the beach, it is no surprise that an increase in elevation just north of the dump sites can be seen. Once an area of erosion (85-89), it is now accumulating sand quite rapidly.

There are a number of ways that we might wish to isolate areas of change. Here we will look at areas that underwent extreme erosion during any interval and areas that on average eroded across all intervals. These approaches should give additional insight into the character of change along the beach.

Analyzing Areas of Extreme Erosion

Finding areas of extreme erosion during any interval will involve reclassifying the three change images to Boolean images, and then finding their logical *or*.

We will use Edit and ASSIGN to reassign the change images, such that areas with erosion of greater than one meter are reclassified to 1 and everything else becomes 0.

u) Open a new values file in Edit, calling it EXTR. Select integer for the data type. The left column will contain the old values of areas with erosion greater than one meter and the right column will contain the new value of one to be reassigned to those areas. The remaining values with erosion less than one meter will be automatically reassigned to zero if omitted from the new values file EXTR. Since we want these values to have a new value of zero, we will leave them out.

v) Next run the ASSIGN module using each CHNG image as the feature definition file to be reassigned with the new EXTR attribute values file. Call the resultant images EXTR8589, EXTR8990, and EXTR9091.

w) Run OVERLAY with two of the EXTR images choosing the maximum option. Call this intermediate result INTERMED. Then run OVERLAY with the maximum option again, using INTERMED and the remaining EXTR image as the two input images. Call the new image, which represents the logical *or* of all three of the EXTR images, EXTRALL.

Although this has produced a rather fragmented image, we can see that there are some solid areas of extreme change, areas that we might wish to examine more closely. The procedure to isolate large solid areas of extreme change involves grouping contiguous pixels into like categories, finding the area of each new group, and reclassifying such that the smaller groups disappear. What remains are the most significant areas of erosion, areas which we can then examine more closely using a time profile.

x) Run the module GROUP using diagonal links and ignoring background on EXTRALL and call the image of discrete groups EXTRGRPS. Now run the module AREA on EXTRGRPS and choose to create an area image (in square meters) called EXTRAREA.

Every pixel in this image will have a value equal to the area of the category in which it is grouped. However, because we are interested only in a specific range of areas we will use RECLASS to reclassify EXTRAREA

y) Run RECLASS on EXTRAREA such that all areas below 5000 square meters become 0, areas between 5000 and 25000 become 1, and areas greater than 25000 (up to some very large number) become 0 also. Call the resulting Boolean image EXTRBOOL.

6. *Why not just make areas above 25000 square meters equal to 1?*

These areas will now be used to construct a time profile of mean surface elevations. The module PROFILE produces a line graph for each of the areas of interest showing any number of summary statistics for each area. We will look at mean elevation as a way to trace the brief history of erosion in these spots. However, before running PROFILE the Boolean image of erosion areas needs to be an image of discreet areas once again. Otherwise only summary statistics of the single category will be produced.

z) To do this, run the module GROUP on EXTRBOOL and call the result EXTRGRP2.

From the histogram of EXTRGRP2, it should be clear that other categories that we are not interested in (tiny interior "holes") were also created.

aa) Examine the EXTRGRP2 image using Cursor Inquiry Mode and find the identifier for each of the 5 large areas we are interested in. Then use Edit and ASSIGN to reassign them to the values 1-5. Call the result EXTRSPOT.

ab) Next, using Create TSF from the File menu, we need to create a time series file called SURFTIME containing the four surface images: SURF85, SURF89, SURF90 AND SURF91.

ac) Finally, run the module PROFILE from the GIS Analysis/Change/Time Series menu over time, using the mean option, EXTRSPOT as the file of profile sample spots, and your time series file.

We can see from the profile that all five areas experienced extreme erosion from 1985 to 1989. Between 1989 and 1990, however, the pattern of erosion changes. The northern three areas appear to stabilize while the remaining areas show a dramatic increase in elevation. From 1990 to 1991 the northern three stay stable (more or less) while the two areas to the south show a dramatic decrease in mean elevation.

7. *What might account for this pattern of erosion and accumulation? (Hint: Display EXTRSPOT and choose the Add Layer option in Composer to see the vector file LINES.)*

Analyzing Areas of Average Erosion

Finding areas whose average elevation has declined from 1989 to 1991 will involve a set of steps similar to the previous section. First an image of average change will be constructed from the difference images produced earlier. This will then be grouped into an image of discrete contiguous areas which can be reclassified to weed out small parcels. The remaining areas will serve as the profile sample spots for another time series profile of mean surface elevation.

ad) Using the module OVERLAY, add together the three difference images DIFF8589, DIFF8990, and DIFF9091. (Note that only two can be added at a time, use a temporary intermediate image.) Call the result DIFFADD.

ae) Divide DIFFADD by 3 with the module SCALAR. Call that image of average change AVERCHNG.

Areas that, on average, eroded for the entire period will have a negative value while the rest of the image (areas of overall accumulation, including the background) should be positive.

af) RECLASS the file AVERCHNG such that areas between -10000 and -20 cm (the latter is the cut off for significant change) are set to 1 while the rest of the image is set to 0. Call the new Boolean image of areas that eroded on average AVEREROD.

ag) To weed out the smaller contiguous parcels in this image, run GROUP on AVEREROD and call the result AVERGRPS. To find the area of each discrete group, run the module AREA (choose the square meter option) on AVERGRPS and call the new image AVERAREA.

ah) Then RECLASS the file AVERAREA such that areas exceeding 2000 square meters become category 1 and all others become 0 (remember to account for the background group as in the previous section). Call the new image of large areas only AVERBIG.

ai) Before this image can be used in the PROFILE module, each area must again be assigned a unique identifier. Run GROUP on AVERBIG and call the new image of areas with unique identifiers AVERUNIQ.

aj) Unfortunately, as before, there are "holes" within the large groups that were also counted as unique groups. To fix this, run HISTO (set the minimum display to 1 instead of 0) and jot down the identifier of the ten largest groups. Then use Edit and ASSIGN to reassign the ten largest groups in AVERUNIQ to the values 1-10 (let the others default to 0). Call the final image of sample spots AVERSPOT.

ak) To see the change over time in mean elevation of the sample spots in AVERSPOT, run the module PROFILE with AVERSPOT and use the time series file of surface images from the previous section.

The resultant graph shows 10 profiles of elevation, some of which look familiar. Groups, such as 6 and 9, are nearly coincident with areas in the previous profile and exhibit similar profile patterns (steep/stable down to 1990, steep up to 1991). However, other groups such as 1, 4, 5 and 6 are interesting because of their steady decline; these are areas missed in the previous analysis because they exhibit no extreme decline in any one year. It is also worthy to note that the areas of average erosion are substantially larger than the areas of extreme erosion. This is significant if the object is to stabilize the entire beach and not just patch up the most badly eroded stretches.

8. *Using procedures demonstrated throughout this exercise, calculate the volume of sand needed to replace that which was lost from 1985 to 1991 in group 4 from AVERSPOT.*

Summary

Both change images and time profiles appear to be powerful tools for analyzing coastal erosion. They can clearly be used to make recommendations concerning the locations of sand replenishment projects as well as the volumes of sand needed. However, many criteria were not considered in our analysis. Other research questions may have led us to isolate areas near roads or parcels of land publicly owned as the sites for our time profiles. Or perhaps an interest in the disappearance of seagrass may have prompted a closer look at offshore data. We may have even used the data to argue against sand replenishment projects. In any case, the tools demonstrated should prove useful to the analysis of coastal elevation and bathymetry data.

Special thanks to David Goodwin of the Department of Environment and Planning, Adelaide, South Australia for providing the data set for this exercise as well as a number of publications that made interpreting it possible.

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Exercise 6: Modeling the Impact of Sea Level Rise in Narragansett Bay, Rhode Island

Shoreline recession is a major concern to resource and environmental managers in many coastal areas of the world today. Coastal retreat is resulting from the constant pounding of the coast by active waves, continued subsidence of the coastal regions, and rising sea levels. All such processes contribute to the erosion and flooding of low-lying coasts. The impact of a substantial sea level rise is often negative but may be beneficial. It could be devastating to beaches, wetlands, agricultural and urban lands located along the coasts. The negative consequences can be minimized and the beneficial effects enhanced with proper planning if the dynamics of sea level change are understood.

Many scientists believe that increasing levels of carbon dioxide and other greenhouse gases will lead to continued global warming and that this warming will in turn lead to increased melting of ice sheets and glaciers, causing global sea levels to rise. Recent years have seen an increasing number of publications supporting this global warming and sea level rise hypothesis.[1] Hoffman et. al. (1983), for example, project that global sea level rises ranging between 1.8 feet (low scenario) and 11.3 feet (high scenario) would affect all coastal areas by the year 2100. (However, it should also be noted that there are some scientists who reject the idea of global warming altogether. They point to the uncertainty present in the indicators used to predict global warming and subsequent rises in sea levels.)

In this exercise, we will model the extent of coastal flooding given a predicted sea level rise for an area near Tiverton, Rhode Island, USA, where the Sakonnet River empties into the Atlantic Ocean. There are several ways to explore future coastal flooding and in this exercise we will use both visual and quantitative techniques. In the first part of the exercise both techniques will be used in a straight forward manner to illustrate coastal flooding and the areal extent of particular landuse types affected. The second part of the exercise goes beyond the traditional Boolean analysis to briefly explore the effects of uncertainty in the database on the decision making process.

Part 1: The Impact of Sea Level Rise

Our task as GIS analysts is to determine which parts of the study area will be flooded by the year 2100 given a global sea level rise of 1.9 meters. This figure is the average of ten published sea level rise estimates. We will also determine the areal extent in hectares and percentages of each landuse type affected by the rise in sea level. Two images are available to us for these analyses -- a digital elevation model (DEM) in meters above sea level; and a landuse map showing 13 landuse types covering the study area.[2]

a) Set your Working folder to that which holds the data for this exercise (e.g., \UNITAR\CZ\Data\Exer6). Then use DISPLAY Launcher to view RIDEM, the digital elevation model. Use Cursor Inquiry Mode to check some of the data values.

The Sakonnet River is represented by those pixels with the value zero -- zero meters above sea level. The Atlantic Ocean is approximately four kilometers to the south of the southernmost part of the image. Because of the wide river mouth and the proximity of the ocean, the section of the river in the study area behaves very much like an ocean bay, with water levels rising and falling with ocean tides. We will refer to this section of the river as "ocean" in the remainder of the exercise.

b) Now use DISPLAY Launcher to view RILANDU, the landuse image. This image was originally derived from aerial photographs.

c) To get a better idea of what the area looks like, we can display the elevation model three dimensionally, with the landuse information draped over the top. To do this, run the module Fly Through, giving RIDEM as the surface

1. See, for example, Barth and Titus (1984) and National Research Council (1990).

2. The data for this exercise was supplied by the Department of Natural Resources Science, University of Rhode Island. It was produced from the RIGIS digital database and is considered the intellectual property of the University of Rhode Island.

image and RILANDU as the image to be draped. Use the Qualitative palette.

We will address the quantitative questions of landuse types and areas to be inundated. To determine the flooded area, we will create two Boolean images, one showing the flooded area of 1993, and the other showing the predicted flooded area of 2100. Then through overlay subtraction of these two images, we will be left with the area flooded due to the 1.9 meter sea level rise.

d) To begin this analysis, use the RECLASS module with RIDEM according to the following reclassification parameters and call the resulting image LAND1993.

New value	Old values from	To those just less than
0	0	0.1
1	0.1	999

LAND1993 is a Boolean image in which land areas (including the inland lake) have the value 1 and ocean areas have the value 0.

e) Now use RECLASS again with RIDEM to create a similar image showing predicted land and ocean areas for the year 2100, given a 1.9 meter sea level rise. Call the resulting image LAND2100.

1. What values should you use in the reclassification to create LAND2100?

f) We can make a visual estimate of the impact of future flooding by viewing a crosstabulated image of LAND2100 with LAND1993 and draping it over the original DEM with the module Fly Through. Run the module CROSSTAB with LAND2100 as the first image and LAND1993 as the second image, calling the output image CROSLAND.

g) Use Fly Through and drape CROSLAND over the elevation model RIDEM with the Qualitative palette. Notice the areas that do not overlap. These are areas that we can visually estimate will be flooded with a 1.9 meter sea level rise.

h) Look at LAND2100 again with DISPLAY Launcher.

Notice that there are some areas in LAND2100 that are identified as ocean, but are physically separated from the ocean. These are areas that lie below the predicted sea level, yet because of the surrounding topography, the rising ocean water will not be able to reach them. In fact, it is only those ocean areas in LAND2100 that are connected to the original water source that will be flooded. In order to correct LAND2100 for these low-lying yet non-flooded areas, we will use a connectivity operator called GROUP.

The IDRISI module GROUP assigns a new identifier to a pixel based upon that pixel's value in relation to the values of its immediate neighbors. GROUP moves through an image, beginning in the upper left corner, and assigns group identifiers sequentially, beginning with 0, to groups of pixels that are contiguous (i.e., share a common boundary) and have the same identifier. We may choose to consider only the four pixels that share a full side with the pixel of interest, or we may also include the four diagonal pixels that share only corner points with the pixel of interest. These corner point connections are referred to in IDRISI as diagonal links. In our case, we are concerned with the flow of water from one pixel to another and thus, we will assume that diagonal links between ocean pixels do allow for the flow of water.

i) Run the module GROUP with LAND2100 and call the resulting image GROUPS. Select to use diagonal links and uncheck to ignore background. In the output image, use Cursor Inquiry Mode to examine some of the values.

2. Which group represents the ocean in 2100?

We may now make a new image showing land and ocean areas for 2100 by reclassifying the group numbers in GROUPS. We want to create a Boolean image in which the ocean has the value zero and the land areas have the value one.

j) Use the module RECLASS with GROUPS to create this new image, and name it TEMP. Examine TEMP with DISPLAY Launcher to make sure it is what you expect. All the ocean pixels should be connected, at least by a corner point. This is the correct image for land in 2100. To delete the old image named LAND2100, in the Files tab of IDRISI Explorer, select LAND2100 in the file list and left-click. Hit the Delete option. Then select TEMP in the window, left-click, and select Rename, calling it LAND2100.

We are now ready to examine the difference between the ocean extent in 1993 and that predicted for 2100.

k) Isolate the areas that were land in 1993, but changed to ocean in 2100 by using the OVERLAY module to subtract LAND2100 from LAND1993, producing the output image FLOOD.

l) Then run the module AREA on FLOOD and indicate that you want tabular output in hectares.

> 3. *How many hectares of land will be flooded by the year 2100?*

Now that we have isolated the area to be flooded in 2100, we will determine the area of each specific landuse type that will be lost to floods.

m) Use the OVERLAY module to multiply RILANDU and FLOOD. Call the result FLOODLND. Run the module AREA on FLOODLND and ask for tabular output in hectares.

> 4. *List the landuse types and the number of hectares of each that will be lost to flooding.*

We may also determine the percentage of the flooded area contributed by each landuse type. This calculation could be done easily by hand in this case simply by dividing the areas found in question 5 by that found in question 4 and multiplying by 100. But if the number of landuse categories was very large, time could be saved by automating the procedure. By creating area images rather than tabular output, the percentage calculations can be performed using the GIS rather than calculating by hand.

n) Run the module AREA again with FLOOD to create an area image called FLDAREA. Display this image and use Cursor Inquiry Mode to verify that the value of all the pixels in the flooded area is the same as what you found for question 4. Likewise, run AREA with FLOODLND to produce the area image LNDAREA.

o) Now to calculate the percentages, use the module OVERLAY to divide LNDAREA by FLDAREA to produce the image RATIO. To turn these ratios into percentages, use the module SCALAR with RATIO and multiply by 100. Call the result PERCENT. Each pixel's value in the flooded area of this image is the percentage its landuse category contributed to the entire flooded area.

p) To produce the tabular information that we want, use the module EXTRACT with FLOODLND as the feature definition image and PERCENT as the data image. You may use the MIN, MAX or AVERAGE statistics since they will all produce the same result.

> 5. *Why does category 0 show a value of 100%? Which landuse makes up the largest percentage of the flooded area?*

It may also be interesting to determine what percentage of each landuse type in the entire study area will be lost to flooding, since losing a significant proportion of a rare landuse, such as wetlands, might be more critical than losing a small proportion of a common landuse, even if the latter were to lose more in total area.

q) Calculate the percentage of each landuse in the study area that will be lost to flooding using an automated procedure.

> 6. *What steps did you use to find these values? List all the landuse types in the study area and the percentage of each that*

will be lost to flooding.

r) Finally, prepare a new DEM and landuse image that represent the year 2100. Use these to create a three dimensional display depicting the study area in the year 2100.

7. *What steps did you need to take to make the new DEM? The new landuse image?*

Part 2: Incorporating Uncertainty

In Part 1, we made some assumptions that influenced the outcome of our analysis. We assumed that the elevation data we used were perfectly accurate. There is, however, uncertainty in the digital elevation model due to error in the original paper map and in the digitization process. Thus when locations have values near a threshold, in our case 1.9 meters, there is uncertainty about whether they do or do not exceed that threshold.

In this part of the exercise, we will look briefly at a method for incorporating uncertainty into GIS analyses. Here we will explore how uncertainty in the digital elevation model might affect the estimate of ocean areas in the year 2100 as shown in LAND2100, assuming a 1.9 meter rise in sea level (Note that there is also uncertainty in the sea level rise estimate. This source of error won't be treated here). For a further discussion on uncertainty and error in decision making, refer to the IDRISI Manual.

In Part 1, we used simple Boolean analysis to estimate the extent of sea level rise based on a hard decision rule, i.e., 1.9 meter rise in sea level by the year 2100. If we are to assume that there is error in the database, however, then for any location a whole range of values are possible, the recorded value being only one of the possibilities. In this case our hard decision rules may not be meaningful. Soft decision rules are needed that accommodate uncertainty in the database.

In our case, a soft decision rule will be in terms of the *probability* with which each pixel exceeds or is exceeded by 1.9 meters, and not the hard decision rule as to whether each pixel's recorded value exceeds or is exceeded by 1.9 meters. In LAND2100, there are only two possible values -- zero for ocean areas or one for land areas. The image we will create in this part of the exercise will have values that range smoothly from zero to one and represent the probability that each pixel will be ocean in 2100. Given this probability, we will then decide upon the level of risk we are willing to accept and will create a Boolean flood map accordingly.

Before proceeding with calculating the soft decision boundary, we need some way of characterizing the level of uncertainty in the digital elevation model. The value error in RIDEM has already been calculated as 4.559 meters. This is the RMS (root mean squared) error and describes the variability of the possible elevations about the recorded elevation for each pixel. In IDRISI, the RMS error is documented in the "position error" field in image and vector documentation files.

s) Using IDRISI Explorer, examine the metadata for RIDEM to verify that the value error field has the value 4.559.

To evaluate the soft decision rule, the module PCLASS is employed. PCLASS evaluates the probability that each recorded value exceeds or is exceeded by a specified threshold. To do this it asks for the file to be evaluated, the value of the threshold, and whether you want to evaluate the probability of pixels exceeding or being exceeded by the threshold. It then looks at the value error recorded in the documentation file of the image and constructs about each value in the image a normal distribution with a mean of 0 (i.e., it is assumed that the image is unbiased) and a standard deviation equal to the RMS error. It then finds the location of the threshold within this distribution and integrates the area under the curve. This area is the probability that the pixel value either exceeds or is exceeded by the threshold.

In our case, the threshold value is 1.9 meters and we are interested in the probability that pixels exceed this threshold, i.e., will be land in 2100. Obviously, pixels that have very high recorded elevation values will have high probabilities of having true values that are above 1.9 meters. Pixels with recorded values near or below 1.9 meters will have very low probabilities of having true values greater than 1.9 meters.

t) Run PCLASS from the GIS Analysis/Database Query menu using RIDEM as the input image and DEMPROB as the output image name. Choose to evaluate the probability that each data cell in the image is *greater than* the threshold of 1.9 meters. Use Cursor Inquiry Mode in the output image to examine the pixel values.

Note that all the values range between zero and one, representing probabilities 0% to 100% that a pixel will be above sea level in 2100. For example, a data value of 0.75 means that the pixel has a 75% chance of being above sea level in the year 2100.

In order to create a Boolean image showing ocean and land areas, we must determine what level of risk we are willing to accept. This will often depend on the perspective of the person doing the analysis. For example, a local conservation commission might want to make decisions based on a probability of 50% or higher of being above sea level, while a local planning board may need to make decisions based on a probability of 85% or higher. The determination is based on the amount of risk that is acceptable, or in other words, how bad the consequences of being wrong might be.

Let us make a Boolean ocean and land image based on a 75% probability that areas will be above sea level.

u) Run the module RECLASS with DEMPROB as follows:

New value	Old values from	To those just less than
0	0	0.75
1	0.75	1

Call the resulting image LAND75 and display it.

The pixels with value 1 in this image show those areas that have a 75% or higher probability of being above sea level in 2100. The pixels with value 0 show those areas that have a less than 75% probability of being above sea level in 2100.

8. What are the areas of land and ocean in LAND75? How does this compare to the result you get when you use a reclassification without accounting for error?

9. How does the lack of bathymetric data in RIDEM affect the analysis of Part 2?

Clearly the incorporation of error in analyses using GIS not only makes the process more complex, but also requires the decision maker to think explicitly about acceptable levels of risk. While this is a more difficult process, it is much better than the two alternatives that have prevailed until recently -- to ignore uncertainty in the data and accept the subsequent GIS analyses as "truth," or to disregard the results of GIS analyses completely because "the data are not accurate."

We would like to thank very much the people at the Department of Natural Resources Science, University of Rhode Island who made the data for this exercise available. In particular, Libby Bishop, Peter August, Chuch LaBash, and Margi Latta were very encouraging and helpful.

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Exercise 7: Aquaculture Suitability in the Gulf of Nicoya, Costa Rica

This exercise is based upon a study done by J.M. Kapetsky, L. McGregor, and J. Nanne E. (1987) to assess the suitability of aquaculture in the Gulf of Nicoya on the west coast of Costa Rica. That study focused on a variety of environmental factors and considered three types of potential aquaculture. The data set[1] available to this exercise is only a portion of the data actually used by J.M. Kapetsky, et. al. and the analyses done here are only a subset of those done in the original study. The original study is an excellent example of the range of data and types of analyses that can be done using GIS in coastal zone research.

The exercise that follows utilizes data and performs analyses that are perhaps representative of the fundamental operations available through GIS for coastal zone research. The following exercise is broken into four sections. The first three correspond to each type of aquaculture to be considered and, although the primary focus in this exercise is upon the basic GIS operation of overlaying, the last section will present and discuss additional operations.

Overlaying involves layering a variety of data in such a way that individual layers can be combined with other layers to reveal new information, or query previously hidden information. This information is often insightful and sometimes vital to a particular research project. In the sections that follow, overlaying will be the main GIS tool used to determine the location of possible aquaculture sites in the Gulf of Nicoya. Given data on bathymetry, salinity, landuse, land cover, soil type, and road networks a variety of images will be derived. These images (which were more complete and of a higher quality in the original study) can then be used to make preliminary resource and development decisions concerning aquaculture.

The first section of the exercise considers the suitability of the gulf coast for three forms of aquaculture: intertidal, subtidal, and suspended. Intertidal areas are those areas that are between land and the gulf waters at Mean Low Water. Subtidal are those areas that are between 0 and 5 meters deep in our bathymetry data (note that 0 is used because bathymetry is measured from the Mean Low Water). And areas for suspended aquaculture are those that are deeper than 5 meters, where shellfish could be suspended from floating rafts on ropes or fish could be suspended in cages. Clearly, bathymetry will be the main data layer to consider. It will be combined, using overlay operations, with other data to find those areas that meet a number of criteria considered important for this type of aquaculture development. Also, batch files will be introduced in this section as a way to perform a series of unusually tedious operations.

The second and third sections also depend heavily on overlay operations to find aquaculture suitability. However, some of the layers needed for the overlay operations in these two sections will have to be created using other GIS tools. In particular, the second section involves the determination of shoreline complexity as a variable to assess the possibility of using solar salt ponds (salinas) as shrimp aquaculture sites. Complexity is used as an indication of the relative abundance of naturally occurring shrimp that might seed the ponds. An index for shoreline complexity will be derived from the base data provided. It will become yet another data layer for this suitability analysis.

Section three of this exercise continues with the overlay and suitability themes but incorporates the derivation of new data layers based on proximities. Here the suitability of semi-intensive shrimp culture on the shore itself is considered. This type of aquaculture is obviously dependent upon the availability of water (fresh and salt), where availability will be seen as a function of proximity. A new data layer that isolates areas that are both close to the saltwater mangroves and freshwater rivers will be derived and incorporated in the overlay suitability analysis.

The last section of this exercise will utilize a module that calculates cost distance along networks. This application will enable us to incorporate distance to market along transportation routes as yet another consideration in aquaculture siting. It can be used to complement all of the above analyses -- incorporating another potentially vital piece of information.

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1. The data for this exercise was made available by the United Nations Environment Programme, Global Resource Information Database project (UNEP-GRID), Geneva.

Before proceeding, it might be beneficial to first examine the data set provided for this exercise.

a) Set your Working folder to that which holds the data for this exercise (e.g., \UNITAR\CZ\Data\Exer7). The files needed are listed below and should be examined using DISPLAY Launcher and Metadata.

In addition, run HISTO and AREA on LANDUSE and calculate the relative extent of different landuses and vegetative cover for the areas surrounding the gulf.

BATHYMET - Bathymetry for the gulf waters in three intervals and mangroves.

SALINITY - Salinity estimated in parts per thousand.

LANDUSE - Derived from the land cover classification.

ROADS - Local roads surrounding the gulf digitized from PAIGH[2] maps.

RIVERS - Major rivers entering the gulf digitized from PAIGH maps.

EX7ANS1, 2, 3 - Answer images equivalent to LANDAQUA, SEMINTEN, and ALLMG respectively.

PUNTAREN - Location of the city of Puntarenas, Costa Rica

1. *What percent of the study area is covered in mangroves, forests, and grasslands? What percent is used for agriculture? (Exclude the background area during the calculation.)*

Part 1: Locating Sheltered Areas

Suitable sites for various types of aquaculture are here defined by the degree to which they are sheltered, site salinity, and bathymetry. J.M. Kapetsky, et. al. provide guidelines for determining what represents a suitable aquaculture site and what does not given these variables.

Areas sheltered from the high winds and waves are vital to successful aquaculture and are, therefore, an important part of our suitability analysis. The most obvious sheltered areas are those that have naturally occurring vegetation on them or between them and the open ocean. In particular the mangrove forests of the gulf offer excellent protection for at least intertidal aquaculture. They also have other characteristics that are beneficial to the success of aquaculture (e.g. high productivity, naturally occurring seedstock, accessibility, and inexpensive site acquisition). Mangrove areal extent can be found on the landuse data layer that was developed by J.M. Kapetsky, et. al. from the Landsat image. But because we are interested in areas that are both within and behind mangroves, a simple reclassification of the landuse layer will not suffice.

Finding Covered or Sheltered Mangroves

We must first start with an image, derived from our landuse data, that is classified into water (including intertidal areas), solid land, and mangroves. Then in order to isolate the areas that are either mangrove covered or sheltered from the open ocean by mangroves, we group all contiguous pixels into separate categories. Those areas which are neither land nor contiguous with the open gulf waters must then be either mangrove covered or sheltered.

We will use several modules to do this. First, we use the ASSIGN module to reassign LANDUSE into the three categories of water, land, and mangroves. Next, we run GROUP to assign each group of contiguous pixels a unique value. This will separate the open bay water from inland water bodies into separate categories. It is then possible to isolate open water areas by using the ASSIGN module again. We use OVERLAY to subtract this area from our water, land, and mangroves

2. Pan American Institute of Geography and History, Hemispheric Map Series-1:250,000, The Unified Hemispheric Mapping Program (1981).

image in order to find those areas that are mangrove covered or sheltered.

The ASSIGN module utilizes an attribute values table that consists of a column of old values and a column of the new values to which the old values will be reassigned.

b) Build an integer values file using Edit that looks like the following (note that the file should only contain the two columns of numbers and not the text) and call it TMPMANGS:

0 0	(background - background)
1 1	(water - water)
2 2	(rangeland - land)
3 2	(pasture - land)
4 2	(agriculture - land)
5 2	(dec. forest - land)
6 2	(con. forest - land)
7 1	(salinas - water)
8 2	(clouds - land, the only clouds in the image occur over land)
9 1	(shrimp ponds - water)
10 1	(marshland - water)
11 3	(mangroves - mangroves)

c) Run the module ASSIGN using LANDUSE and TMPMANGS and call the new image of water (1), land (2), and mangroves (3) TMPMANGS (it is appropriate to have different type files with the same name because they will have different filename extensions).

d) In order to isolate those areas that are mangrove or protected by mangroves, begin by running the module GROUP on TMPMANGS and call the result TMPGRPD. Use diagonal links so that any pixel diagonally attached to another with the same category value will be grouped together. This will create an image with a separate identifier for each contiguous group of pixels, one of which will be water open to the gulf. Use Cursor Inquiry Mode to find the z-value for the open water group. If necessary, go back to the image LANDUSE to find in which general area to search.

e) Next, use ASSIGN (similarly as above, note that categories not specifically reassigned will default to a value of zero) to give a value of 1 to the open water group and zero to everything else. Call the new image TMPWATER.

f) Now use OVERLAY to subtract TMPWATER from TMPMANGS (this will cause the gulf waters to revert to the same value as the background value, zero). Call the new image TMPSUBED.

g) Finally, use RECLASS on TMPSUBED such that mangroves and discontinuous water areas will be combined in category 1 and renamed suitable (i.e., areas suitable for aquaculture). Call the new image SUITABL1. It is the result of applying our first limiting factor to defining the areas of the gulf which might be suitable for aquaculture.

Finding Other Sheltered Areas

The image resulting from the above procedure represents only one way to isolate areas that are sheltered. J.M. Kapetsky, et. al. explains that there are other areas that might be sheltered that are not a function of mangroves but of potential wave heights. It can be established that if a given area is unlikely to have wave heights above some threshold, then that area can be considered sheltered and also suitable for aquaculture.

Areas protected from large waves are derivable from knowledge of the gulf's dominant wind patterns and water depth. The most prevalent winds in the gulf blow from either the north or south and can reach speeds up to 37 kph. J.M. Kapetsky, et. al. uses a relationship between wind speed, water depth, and distance from the shoreline to calculate potential wave heights. Here the shoreline is either the land/water interface or the mangrove/water interface. This is because wave generation due to wind is as unlikely within the mangroves as it is on land. J.M. Kapetsky, et. al. found that with a wind speed of 37 kph and a maximum water depth of 6 meters, a distance from the shoreline of no more than 2 nautical miles (3.7 km) was needed to keep waves within an acceptable height limit of 0.4 m. From this, we can assume that those areas within 3.7 km directly north *and* directly south (the direction of the gulf's strongest winds) of the shoreline can be considered sheltered and appropriate for aquaculture.

To find these sheltered areas we will employ a dispersion routine to model the movement of wind due south and due north of the shorelines. The distance criterion specified above requires the creation of a buffer zone 3.7 km wide (obviously several pixels wide). We know from the documentation files that the distance represented by a single pixel (north to south) is 120 m. Therefore, we need an image flagging 31 pixels (3700m/120m) of open water due north and due south of the shoreline (note that enclosed water has already been defined as sheltered).

h) First we will need to create a Boolean image containing the shoreline. This will become the source image from which to model wind movement. To do this, use RECLASS on TMPSUBED, creating an image called TMPSHORE that has just two categories -- open water/background = 0 and leeside (land and sheltered areas) = 1.

Before running the dispersion routine DISPERSE, two other images are needed. To simulate a wind, we need a magnitude image and direction image for the wind. Since we simply want the wind to move according to a specified number of cell units, we will choose a magnitude of 1 (1 cell unit per unit time). For a direction image of winds blowing from the north we need an aspect image containing values of 0 degrees, and for winds blowing from the south, we need an aspect image containing values of 180 degrees.

This will require using INITIAL three times to create a magnitude image and the two direction images.

i) For the magnitude image, use the module INITIAL to create a file called MAG1 that is in byte binary format. Enter the value of 1 as the initial value of the image. Select to copy the parameters for the image from TMPSHORE. Run INITIAL two more times to create the direction images ASPNORTH and ASPSOUTH, but this time select to have them in real binary format (necessary for use with DISPERSE), and to have values of 0 and 180 respectively.

j) Now run the DISPERSE module from the GIS Analysis/Distance Operators menu. The source feature image is TMPSHORE, MAG1 is the anisotropic force magnitude image and ASPNORTH is the anisotropic force direction image. Anisotropic frictions are those frictional elements that have different effects in different directions. Since we want to model a force acting in one direction, due north, as opposed to isotropically, the dispersion routine is appropriate to model wind. For the directional bias, choose the cosine function. The exponent used affects the extent to which a force acts fully or partially for varying directions.[3] We want to ensure that a force of 1 is acting fully at any direction (although we have specified only one direction). Therefore, enter a value of 100 for the exponent. The maximum distance should be set to 31 for 31 cell units. There is no isotropic fric-

3. See the module description for DISPERSE in the IDRISI Help System as well as the discussion of Anisotropic Cost Analysis in the IDRISI Manual for further explanation.

tion image. Call the output image TMPNORTH. Depending on the hardware in use, DISPERSE may take some time to finish. When it does, run the module again using ASPSOUTH instead, and call the output TMPSOUTH. Then, look at the results.

You will notice that each cell records the number of cell units of each step of the buffer as the buffer grows. When the buffer grows beyond the 31 cell units (or 3700 m), then the pixels take on a value of -1. We need to create Boolean images of these two maps by reclassifying values 1-31 to 1 and values of -1 to 0.

k) Do this using RECLASS, and call the outputs NORTH and SOUTH.

To create the suitability map which shows *both* the sheltered mangrove areas and the new open water category, there are two steps. It is the intersection (areas sheltered by shorelines immediately north *and* immediately south) that we are interested in finding.

l) Use OVERLAY to multiply the NORTH and SOUTH images together, and call the result TMPNOSO. It will be the logical intersection of our two buffer zones and, hence, it will be all areas sheltered from high waves generated by the gulf's strong northerly and southerly winds.

m) To combine these newly found sheltered areas with those areas sheltered due to mangrove forests, use OVERLAY to cover TMPNOSO with SUITABL1 such that the area suitable for aquaculture (category 1) is extended to include the newly found 3.7 km north/south buffer zone. Call the new image SUITABL2.

We now have our final "sheltered" data layer.

Incorporating Salinity

Another data layer that would further define suitable areas for our three types of aquaculture is salinity. Salinity plays an important role in aquaculture but is somewhat more difficult to incorporate because of its seasonal variance due to river runoff etc. However, a rough estimate of minimum annual surface salinity is provided for this exercise. Assuming that salinities should not be too low at any time of the year, we can reclassify and overlay to further narrow the area best suited for aquaculture. The optimum range for shrimp aquaculture (just one of our aquaculture possibilities) is between 15 and 25 parts per thousand (ppt). While the data is quite rough and our acceptable range is a gross estimate only for shrimp, it will be sufficient as an example.

n) Use DISPLAY Launcher to examine SALINITY with a legend and a title. RECLASS the salinity data to a Boolean image that isolates salinity levels between 15 and 25 ppt (include 25). Make this area equal category 1 and everything else category 0. Call the new image TMPSALIN.

o) Using OVERLAY, multiply SUITABL2 with TMPSALIN such that sheltered areas within the acceptable salinity range are cut from the suitability layer. Call this new image TMPCUT1. Then use RECLASS to create TMPCUT2 where all the values of 2 are now 0. This eliminates inconsistencies due to a different definition of land in the salinity image.

The area defined in TMPCUT2 represents the areas of the open gulf waters that are sheltered (by our second definition) and that are within the acceptable salinity level. Because the salinity data only covered water open to the gulf and not water within mangroves, we need to recombine the sheltered areas of TMPCUT2 with the sheltered areas of SUITABL1 found previously (we will assume that within all mangroves salinity levels are appropriate for aquaculture).

p) Using OVERLAY, add TMPCUT2 to SUITABL1 and call the result SUITABL3.

This new image shows the combination of sheltered mangroves and sheltered waters within the appropriate salinity level. Category 1 represents the intersection of all our criteria to define suitable areas for aquaculture.

2. *Did limiting aquaculture to this salinity range appreciably reduce the areas available for aquaculture?*

Incorporating Bathymetric Data

The final data layer to consider in this section of our suitability analysis is bathymetry. We will reclassify the areas previously found suitable (due to measures of shelter and salinity) into one of the three bathymetry/aquaculture categories. Then we'll find the area available to each type of aquaculture and try to place the newfound sites in context. This is particularly important for the intertidal area that spans a number of landuse categories.

To reclassify the suitable areas into three aquaculture categories -- intertidal, subtidal, and suspended -- first create an image with those three categories from BATHYMET using RECLASS.

q) In RECLASS, set the categories such that 1 = suspended (> 5m), 2 = subtidal (0-5m), 3 = intertidal (mud and mangroves), and 4 = land. Call the new image of aquaculture types TMPTYPES. (Note: You may want to use DISPLAY Launcher to view the image BATHYMET with a legend to view the current classifications.)

To find the intersection of these categories *and* the areas previously found suitable, we need a Boolean image of those areas previously found suitable.

r) We need to use OVERLAY to multiply TMPTYPES with a Boolean image reclassified from SUITABL3. RECLASS SUITABL3 such that suitable areas and land = 1 and everything else = 0. Call this new image TMPBOOSL and use OVERLAY to multiply it with TMPTYPES to get our final image SUITABL4. Set the legend such that it indicates which aquaculture type is possible in the sheltered areas found.

Interpreting the Suitability Map

Now that the final suitable areas are defined, calculate their areal extent using the module AREA. Choose tabular data in hectares.

> 3. *What is the area available for each of the three aquaculture types? How would you locate only areas above a certain area threshold (e.g., only those areas that are larger than 5 hectares will be considered suitable for aquaculture development)?*

Because we know that the intertidal zone contains a number of different landuse types that have implications for aquaculture, it is important to see aquaculture sites in relation to landuse. One way is to produce an outline of the areas suitable for aquaculture using RASTERVECTOR and to display it on top of a landuse/bathymetry image. Another way would be to create a cross-classification and/or crosstabulation between the landuse and suitability images using the module CROSSTAB.

> 4. *What are the advantages and disadvantages of using the CROSSTAB module? Try it.*

To do the vector overlay procedure, we must isolate the polygons in SUITABL3 that represent areas suitable for aquaculture (category 1) and vectorize them using RASTERVECTOR.

s) Run the module RECLASS and select SUITABL3 as the input file and call the output file AQUAREAS. Assign a new value of 0 to all values from 2 to just less than 999. This will produce a Boolean image where those areas suitable for aquaculture have a value of 1.

t) Now run the module RASTERVECTOR. Select raster to vector and raster to polygon and select to output an IDRISI polygon file. Specify AQUAREAS as the input image and call the output IDRISI polygon file AQUAREAS as well. Check the option to exclude a background polygon of 0. This step will convert the raster image to a vector file that we can display on top of a combined landuse/bathymetry image.

u) To get the landuse/bathymetry image, first RECLASS the water category in LANDUSE to 0 (call the result TMPLAND). Also RECLASS the three water categories in BATHYMET (> 5m, 0-5m, and mangroves) to 12, 13, and 14; mud flats to 1; and land to 0 (call the result TMPBATH).

v) Then use OVERLAY to cover TMPBATH with TMPLAND and call the result LANDBATH. With LANDBATH displayed, use Add Layer in Composer to add AQUAREAS using the Outline White symbol file.

The above analysis only accounts for two of a possibly infinite number of variables that could be used to decide aquaculture suitability. For example, water quality is obviously an important factor to aquaculture development, yet because we do not have the data, it was not part of this exercise. In addition, there are forms of aquaculture that require more specific environments than those defined above. In the next section we will examine one of these more specific cases.

Part 2: Determining Shoreline Complexity

In this second section we will look at another suitability scenario. In the study done by J.M. Kapetsky, et. al., a particular type of shrimp aquaculture was proposed for the already existing solar salt ponds (salinas). Because the 655 hectares (ha) of solar salt ponds are scattered widely throughout the mangrove zone, different ponds will have different potential for shrimp aquaculture. In particular, those ponds that are within clumps of "complex" mangroves will have a higher rate of shrimp productivity due to increased levels of natural seedstocking (high natural shrimp seedstocking has been observed in mangrove zones that have more extensive waterways and current flows). Complexity is the degree to which the mangrove/water interface is convoluted and it is here derived from a measure of the interface length per unit of mangrove area. Obviously, other factors such as salinity, water temperature, and even proximity to roads should also be considered for this type of aquaculture. However, for this exercise, we will only examine pond location and mangrove complexity.

Differentiating Salt Pond Locations

To begin, we need to find and isolate the different groups of mangroves that ring the gulf before calculating shoreline complexity. This initial result will be an image containing each mangrove group uniquely identified with its own value. Those groups below a certain size (in square hectares) will not be included. This image containing differentiated salt pond locations will be derived from the landuse image. It cannot be derived directly, however, and it requires numerous steps in between.

w) Examine the image LANDUSE with DISPLAY Launcher and then reclassify it into a Boolean image of just mangroves (using RECLASS or Edit/ASSIGN). Call the new image MANGROVE. To give each contiguous group of like pixels a unique identifier, use the GROUP module on MANGROVE. Specify that you want to include diagonal links for the grouping process and uncheck to ignore background, and call the output image TMPGRP1.

You will notice, after looking at the image with DISPLAY Launcher, that more than 255 groups are identified and the module must autoscale the image for display. Using cursor inquiry mode, it is possible to see that all independent groups have received unique identifiers, including very small groups.

Actually, there are only a few large groups of mangroves. Also, you might notice that groups of water pixels that were surrounded by mangroves have been given new identifiers different from the very large gulf water group.

> 5. *How might you correct this problem such that all water pixels have the same identifier as the background? Perform that operation and call the result* TMPGRP2.

The image just created should contain groups of mangroves of all sizes with 0 as an identifier for water/background areas.

x) In order to isolate just those mangrove groups that are substantial in size, run the module AREA on TMPGRP2 and choose to create an image of hectares called TMPHECT. Examine TMPHECT with DISPLAY Launcher and decide what cutoff point (in terms of hectares) might be appropriate in order to define the mangrove cluster as significant. Using Cursor Inquiry Mode, move to the smallest size group you want to consider and find its area in hectares (it is suggested that the cluster at the mouth of the Guacimal River with an area of 50 ha be considered the cutoff point). RECLASS TMPHECT such that the larger groups between 50 ha and 4700 ha possess an identifier of 1 and all other pixels have 0. Call the result TMPBIG1.

6. *Why use this range?*

Unfortunately, the identifiers in TMPHECT are area values rather than the previous group identifiers. Because this is not very easy to work with, unique integer identifiers should be given to each group again as in the image TMPGRP1.

y) To do this, use OVERLAY to multiply TMPBIG1 with TMPGRP1 and call the resultant image TMPBIG2. This new image will contain only the larger groups which will now have their original group id numbers. The identifier values for these large groups, however, are still high numbers based upon the original clustering of pixel groups. Rather than using the integer values of TMPGRP1, we can change these id values to have the range of 1-14.

z) The EXTRACT module can be used to extract a values file that contains the old identifiers we want to change. Run the module EXTRACT (select the minimum option) with TMPBIG2 as both the feature definition file and the file to be processed. Call the output values file TMPIDS.

aa) After extracting the file, look at it with Edit. The column on the left shows the id numbers as areas presently associated with each big group of mangroves and the right shows the same. Change the column on the right to have the new identifier values 0-14. Save this change, and then run ASSIGN using the values file TMPIDS to replace the old id numbers in TMPBIG2 with the new ones. Call the output image of mangrove groups numbered 1-14 BIGMANG (and delete all TMP files.)

There is one more step necessary before starting the procedure to calculate shoreline complexity. While BIGMANG contains the clusters that we are interested in, our process has limited the groups to only immediately contiguous pixels. That is, "loose" pixels that clearly belong to a particular group by virtue of their proximity have dropped off the image because they were not touching a main group. We will correct this oversight by classifying "loose" mangrove pixels within 1000m of any of our main groups to that group. To do this we will first find all mangrove pixels within 1000m of any of our existing groups and then reallocate them to the group which is closest.

ab) Run the module BUFFER from the GIS Analysis/Distance Operators menu on BIGMANG. Enter 1000 for the buffer width, 1 for the target area and buffer zone, and 0 for the non-buffer zone. Call the buffer image TMPBUFF and use OVERLAY to multiply it with MANGROVE (the original image of just mangroves from LANDUSE) creating TMPMANG. This image now contains all 14 mangrove groups as well as additional mangrove pixels that are within 1000m of our 14 groups.

These additional pixels need to have an identifier that matches the identifier of the main group with which they are associated.

ac) Run the module DISTANCE on BIGMANG and call the result TMPDIST. Then run the module ALLOCATE using TMPDIST as the distance image and BIGMANG as the target image. Call the new image of pixels allocated to the closest big mangrove group ALLOCATED.

ad) Finally, use OVERLAY to multiply ALLOCATED with TMPMANG to get ALLMG, an image of all the mangroves (both contiguous groups and "loose" pixels) correctly classified to the values 1-14. Make sure that this is correct before proceeding.

7. *How significant is the difference between BIGMANG and ALLMG? What difference might it make to our calculation of mangrove zone complexity?*

Creating the Shoreline Image

As noted above, to find mangrove zone complexity we first need to find the length of a given mangrove zone's shoreline and its area, and then construct a ratio between the two. This will be done here by making a thin (one pixel wide) buffer around the mangrove zones, isolating that part of it which is the mangrove/water interface, finding its area in hectares, and dividing by the number of hectares in its mangrove zone. It is important to note that this procedure was developed only as an illustration of one of the ways to establish a measure of complexity. It is not the work of a specialist (it is not known if this procedure matches that used in the study done by J.M. Kapetsky, et. al.), nor should it be used without close scrutiny.

ae) To construct this second buffer, use the same procedure as above. Run the module BUFFER again, this time on ALLMG. Call the result TMPBUFF2 and enter values such that only the pixel-wide buffer is isolated. (Note: you will need to use a value that is 1 plus the resolution.) It is important to remember that we are not interested in the target area (the mangroves themselves) and we must account for the case where buffer pixels might be attached to mangroves only diagonally.

> 8. *Because distance is calculated differently along the diagonal of a pixel, what range of values will isolate a buffer one pixel wide?*

af) Use the module OVERLAY to multiply TMPBUFF2 with ALLOCATED (from the previous procedure) to get TMPBUFF3 (the thin buffers differentiated according to the mangrove zone to which they belong). However, the buffer does not yet represent the shoreline, it is currently a buffer representing the perimeter (shore-side and land-side) of each mangrove zone. Create an image called TMPLAND by reclassifying LANDUSE into solid land and clouds = 0 and water, salinas, shrimp ponds, marshland, and mangroves (all areas that provide water interface) = 1. Use OVERLAY to multiply TMPLAND with TMPBUFF3 to create TMPSHORE, an image of just the shorelines (mangrove/water interface) of each of the mangrove zones.

Calculating Shoreline Complexity

The last step will be to find the area (in hectares) of the shorelines and divide by the area (in hectares) of the mangrove zones. First, an image showing area values for shorelines is needed.

ag) Run AREA on TMPSHORE and create an output values file by the same name. Use the Edit module with this values file in order to set the area for background, 0, to have a new value of 0. Run the module ASSIGN on ALLMG to change the image values to the new area values using TMPSHORE. Call the new image of pixels identified by shoreline area TMPSAREA.

ah) Another image is needed that contains area values of mangrove groups. Run AREA on ALLMG and this time produce an image file of the total area of each mangrove called TMPTAREA.

ai) Now use OVERLAY to divide TMPSAREA by TMPTAREA to create TMPRATIO, the ratio index of mangrove zone complexity.

aj) Finally, examine the spread of the ratio values using the HISTO module. The module will display the frequency histogram of the complexity values. To improve the display, elect to use a different minimum and maximum so as to drop out the background value from the histogram. Set the minimum to 0.01 and the maximum to 0.62. Use a display class width of 0.01 for a graphic display.

ak) Because there are many categories, we can choose to group them into levels of complexity. One possibility is to group values into three categories: most complex (.55 - .65), complex (.35 - .55), and least complex (.05 - .35). Use the module RECLASS to do this and give these groups new values of 1, 2 and 3 respectively. Call the final image COMPLEX.

9. *Using modules familiar to you by now, fill in the following table. Also calculate the area of the three zones of complexity.*

Mangrove Zone Number	Shoreline Complexity
1.00	
2.00	
3.00	
4.00	
5.00	
6.00	
7.00	
8.00	
9.00	
10.00	
11.00	
12.00	
13.00	
14.00	

Even though this has been a long and somewhat convoluted procedure to develop the information on this table, it might prove invaluable to aquaculture planning. This is particularly true if the complexity algorithm is known to be robust and if it is used in conjunction with the many other variables that will, no doubt, determine shrimp aquaculture suitability.

Part 3: Proximity Measures

In this section we will examine yet a third scenario of aquaculture suitability. Here, semi-intensive shrimp aquaculture on the shore itself will be considered. For the sake of this exercise, suitability will be a function of the availability of fresh and salt water (both are necessary in large quantities for this type of aquaculture). The study by J.M. Kapetsky, et. al. proposed that areas within 1 km of both major rivers (fresh water) and the gulf (salt water) would be ideal. These areas can be easily found by constructing a 1 km buffer *inland* from the coastline, a 1 km buffer on either side of fresh water rivers, and overlaying the results to get their intersection.

al) Starting with the LANDUSE file, make the first 1 km buffer *inland* from the coastline using a procedure similar to that found in the first section. Remember that the coastline is not necessarily the interface with open water, but the boundary between solid ground and all other landuse types (e.g., marshland, mangrove, salinas, etc.). It is suggested that you outline the entire procedure before running any modules. The resultant image should be a Boolean image where the buffer zone = 1 and everywhere else = 0. Call the result COASTBUF.

Producing a 1 km buffer around the fresh water rivers is done in a similar manner except in this case, we will start from a vector image that was digitized from a 1:250,000 map of the gulf region (Dibujado y Litografiado por Instituto Geografico Nacional, Costa Rica). A two-step procedure is used to rasterize the vector file of rivers.

am) Using DISPLAY Launcher, examine the river vector file called RIVERS. To rasterize RIVERS, start by creating an empty raster grid where all image values equal zero. Use the module INITIAL to create a raster file called RIVERS and copy the spatial parameters of the LANDUSE image to represent the same column/row structure and referencing system of the data set. To place the vector rivers into the blank raster file, use the module RASTERVECTOR. Now use this file to produce the second buffer zone needed to meet our criteria. Do this in a similar manner to COASTBUF except call the result RIVERBUF (note that the buffer zone created will be on either side of the river just like it was on either side of the gulf).

an) The final step is simply to use OVERLAY to multiply COASTBUF and RIVERBUF. Call the resultant area suitable for "on shore" semi-intensive shrimp aquaculture SEMINTEN.

10. What is the total area available to this form of aquaculture? Is it evenly distributed around the gulf?

It is important to note that there are other factors that were considered by J.M. Kapetsky, et. al. that have not been addressed here. In particular, they utilized soil and landuse data to further define the areas suitable for this type of aquaculture. It should be clear by now how that might be done given the appropriate data.

ao) Using the modules OVERLAY and AREA, calculate the extent of the various landuse types that fall within the buffer zone suitable for semi-intensive shrimp aquaculture.

11. What might that tell us about the availability of the land for this type of aquaculture development?

This type of proximity analysis is often integral to general suitability studies. It is hoped that the above example illustrates how to utilize distance and reclassification operators to create buffer zones around polygon and line features. However, distance from line features, such as rivers, is only one way to look at proximity. Another method, that will be explored in the final section, is to calculate distance along linear features, such as roads.

Part 4: Distance to Market

In this final section we will employ yet another factor that could be used to judge suitability -- cost distance of traveling along roads to the market along transportation networks. This variable is useful to all of the aquaculture projects examined in this exercise insofar as they will all transport their product along roads and waterways to some market. In this exercise we will assume that Puntarenas is the principal market destination for the gulf's fish although any destination point might be used. It is from this particular market destination that distance along transportation routes will be calculated. The distance computed, however, is not just simple distance along routes (although we can compute that too), it is a weighted cost distance dependent upon how a given route is classified (e.g. secondary roads will "cost" more to traverse than primary roads). This abstract "cost" may be the cost in dollars, labor time, or some other resource used in transportation. Because refrigeration in the gulf region is limited, the time that it takes to transport fish to market is an important consideration. For this reason we will think of cost in terms of labor time in this exercise (note that this section was developed independent of the study done by J.M. Kapetsky, et. al.).

The IDRISI module used for this type of distance calculation is the costgrow option within the COST metaprogram -- read about this module in the IDRISI Help System. To run COSTGROW we will first need to produce a feature definition file. This is simply the file that contains the point or points from which cost distance will be calculated.

ap) Create this image by first using the module INITIAL to create an image of zeros to the dimensions of the LANDUSE image (call it TMPPUNT). Then use the module RASTERVECTOR to rasterize the point file PUNTAREN and change the cells of the raster image to record the identifiers of points. This will be the feature image to be used with Costgrow in the COST module.

The second file needed to run Costgrow in COST is a file that represents the gulf's road network (connected to Puntarenas) in terms of relative frictions or, in this case, time needed to travel 120m (one pixel in our imagery). Each cell that will make up the road and waterway network around the gulf will have a value that represents the labor time needed to traverse that cell. Cells that are not part of the network (i.e. off the road) will represent an absolute barrier to transportation. However, like the river network of the previous section, the road network (digitized from the same base map as the river data) is stored as a vector file, ROADS.

aq) Use DISPLAY Launcher and Metadata to examine this vector file and its route classifications. Rasterize ROADS, as in section 3, and also call the resultant image (of the same dimension as the LANDUSE image) ROADS. Note that the ROADS image is best viewed with the Qualitative palette.

The road classifications in the ROADS image do not yet have attached to them any measure of cost/relative friction. However, we do know the type of road and can estimate relative friction or, in this case, travel time per pixel.

12. *Assuming that the average speeds listed below are correct (in fact, they are guesses for the sake of illustration), calculate travel time in minutes to cross an individual pixel for each road type. Remember that each pixel is 120m square.*

Old Category	Road Type	Estimated Speed kilometers/hour	Relative Friction minutes/pixel
2	2 lanes, paved	60.00	
3	1 lane, paved	35.00	
4	2 lanes, unpaved	35.00	
5	1 lane, unpaved	15.00	
6	dry weather only	15.00	
10	ferry crossing	8.00	

13. *How can we calculate the "dry weather only" category using rainfall information?*

ar) Now use Edit with a real number attribute values file with the old categories in the left column and the new relative friction values on the right. In addition, add a line for the off-road value of 0 and give it a new value of -1 (to represent it as an absolute barrier).

as) Next, use ASSIGN to reclassify the ROADS image into a friction file with the above relative frictions. Call this new image TMPFRIC. Run the module COST from the GIS Analysis/Distance Operators menu and choose the Cost Grow option with TMPPUNT as the feature file and TMPFRIC as the friction surface. Call the resulting cost distance image which shows travel time to Puntarenas TRAVTIME.

To display this image with the images of areas suitable for aquaculture development, it is possible to run an OVERLAY cover operation using TRAVTIME as the cover image. However, because TRAVTIME is a real number image, for its underlying values to display, values in the underlying image TRAVTIME must also be altered.

at) Use RECLASS to do this. The background values in TRAVTIME are -1 and must be reclassified to 0 to function with the cover option. For the suitability image, you can reclassify SEMINTEN for suitable areas to have a value of 300 and 0 everywhere else. The value of the nearest road pixel should give a rough estimate of travel time to market (by road and ferry) from a given proposed aquaculture site.

Summary

In this exercise, we have examined the different ways that geographic analysis might be used in aquaculture suitability analysis. In the first section we saw how basic use overlay and reclassification operations could be usefully combined with a dispersion routine to create new data layers that did not previously exist -- new information on shelter which is vital to aquaculture facilities. The second section was similar in that it also derived new information based on the relationships of each pixel to its neighboring pixels, but in this case it was used to develop a rating of shoreline complexity. The third section incorporated notions of proximity to our suitability analyses and the fourth section did the same but focused on cost distance rather than straight distance. All of the analyses performed are simply meant to demonstrate the possibilities for GIS in aquaculture suitability studies and should not be seen as exhaustive. All suitability studies are contingent upon the robustness of the criteria used to define suitability and the data available for analysis.

We would like to thank very much J.M. Kapetsky, senior fisheries resources officer, FAO Inland Water Resources and Aquaculture Service for allowing us to reproduce a small part of the Gulf of Nicoya GIS/aquaculture project. Also, we would like to thank Ole Hebin, manager, and Ronald G. Witt, systems analyst at GRID-Geneva for supplying us with the data set used in the Nicoya project.

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Exercise 8: Planning for Coastal Development in the Basque Country of Northern Spain

As cultures worldwide draw increasing attention to the relationship between environmental quality and economic development, preserving the visual quality of coastal landscapes is growing in importance. The concerns range from a purely aesthetic desire for preserving the beauty of the coastal landscape to those over the potential ecological impacts of alterations of the landscape. Planners of coastal landscapes, in particular, considering such concerns must integrate different values including the seascape's potential for attracting a sustainable tourist business, expanding residential growth, or pursuing other forms of economic development. The visual priorities placed on a coastal landscape are indeed diverse.

This exercise addresses the issue of sea influence upon the planning and development of coastal landscapes. The development potential of any coastal area depends upon the availability of clear views and access to the sea. It also depends on factors such as the distance from the shore, and the slope and aspect of the land. A detailed analysis of such factors is important for the effective and balanced management of the coastal zone, and a GIS is one tool capable of enhancing the analysis.

The exercise relies on a digital elevation model of a part of the coastal area in the Basque region of Spain. The image is called EADTM (a digital terrain model near the town of Ea).

a) Set your Working folder to that which holds the data for this exercise (e.g., \UNITAR\CZ\Data\Exer8). Then use DISPLAY Launcher to view the image EADTM. The coastline faces northward.

Since commercial and residential development is most likely to occur in coastal areas with a view of the ocean, the first step in this exercise is to identify such areas. To better visualize the terrain from which views of the ocean are likely to occur, we can use a three-dimensional Fly Through display. The module Fly Through accomplishes this.

b) Run the Fly Through module using EASML as the surface image to display. Deselect to use a drape image and use all other default settings. Manipulate the display so that the coastline is revealed.

Part 1: Viewshed Analysis

For this analysis, we use the module VIEWSHED which determines all the surfaces visible from a selected point or set of points. In order to run VIEWSHED, two images are needed--a surface image on which to calculate the view and a viewpoint image containing the points from which the view is determined. In our case, the surface is the digital elevation model, EADTM. We do not have a viewpoint image and need to create one.

Preparing the Data

Calculating viewsheds is a lengthy process. Therefore, a portion of the original study area was selected for the purpose of demonstration. To create the new study area, it is necessary to make a windowed portion of EADTM using the WINDOW module.

c) Run the module WINDOW from the Reformat menu for only one image. Call the output EADTMW and specify Window by row/column positions with column 157, row 119 for the upper-left corner and column 401, row 281 for the lower-right corner. Look at the result.

The next step is to create a viewpoint image containing points from which views will be calculated. There are two methods for creating a viewpoint image. One is by onscreen digitizing points into a vector file that afterwards are rasterized into an image file. The other method involves the updating of values in individual cells. In either case, one needs a blank image of the same column and row dimensions of the digital elevation model. This blank image is where viewpoints then are placed.

d) Use DISPLAY Launcher to view the image EADTMW. With the image on the screen, select the Digitize icon (13th from the left) to invoke the onscreen digitizing option. Enter EAVEC for the name of the vector file to create and select point to indicate that you will be digitizing a point. Take the default of 1 for a feature ID. The cursor now appears on the screen. To digitize, move the cursor to some point in the ocean (not too far from the shore) and press the left mouse button. The feature is drawn on the screen as it is digitized. Next, press the right mouse button to indicate that you have finished digitizing. If you are unsatisfied with the placement of your point, then you can select the Delete Feature icon (the one of the X) next to the Digitize icon to delete the digitized feature. If you are happy with its placement, select the Save Digitized Data icon (the one with the down arrow) to save the digitized data. (Note: You could have selected a point on land, but we suggested a point in the ocean so that both ocean surfaces and land surfaces are captured from the view point).

The ocean point that you have just digitized will be the viewpoint, yet it is still necessary to create an image containing this point. To do this, we will use two modules INITIAL and RASTERVECTOR.

e) Use the INITIAL module to create an image matching the row, column structure and pixel size of EADTMW. Specify PTVIEW as the image to create and select the integer data type. Select the binary format and specify an initial value of 0. Choose to copy the spatial parameters of the existing image EADTMW. PTVIEW is a blank image where all pixels have a value of 0. This needs to be updated to include the viewpoint you have selected. We will use the module RASTERVECTOR for this task.

f) Open RASTERVECTOR and specify EAVEC as the vector file containing the point data and PTVIEW as the image to be updated. Select the option to change cells to record the identifiers of points. The updated image PTVIEW is the viewpoint image needed in order to run VIEWSHED.

Creating the Viewshed

g) Now run the VIEWSHED module from the GIS Analysis/Context Operators menu. Specify EADTMW as the surface image, PTVIEW as the viewpoint image, and VIEW as the output image. Viewer height can be zero or it can refer to the average person's height, average height of buildings in the area, or average height of vegetation. The height selected will depend on the type of view the user is interested in, and the user's knowledge of the area. For now, we simply want to know if surfaces are visible to each other, so choose zero for viewer height. Specify 2000 meters as the search distance. Since the pixel size is 25 meters by 25 meters, the computer will only search a distance of about 80 pixels in all directions for surfaces within view of your points. Select Boolean output type and OK to run VIEWSHED. If you selected your point too far into the ocean, it may well be possible that no land areas exist with view of your viewpoint. If this is the case, either select a point closer to the shore and repeat the above process or choose a larger search distance (3000 meters or 4000 meters) for calculating the viewshed. All values of 1 are the surfaces within view of your point.

1. *Can you tell which surfaces are land and which are in the ocean? In other words, what areas on land have a view of the point that you have selected?*

One way to isolate this view would be to create a mask where land = 1 and sea = 0 and multiply this mask with the viewpoint image.

h) Use Metadata to examine EADTMW to determine it's minimum and maximum values. Now, run RECLASS on EADTMW to reclassify values into a Boolean image. Call the output MASK and choose a user-defined classification. Reclassify all land values (values greater than 0) to 1. Next, use the OVERLAY module and specify MASK as the first image, VIEW as the second image, and LAND as the output image. Select to multiply the two images (First * Second). Now, use DISPLAY Launcher to view the output image LAND. All values of 1 are the land surfaces that have a view of your point.

2. *OVERLAY provides a number of other options for combining two images such as adding or dividing two images. Can*

you use one of these other options to obtain similar results?

Part 2: Determining Panoramic Views

The development of the coastal landscape will most likely take place in those areas of the land that offer panoramic views of the ocean rather than a narrow view of the ocean. To find which areas offer panoramic views of the ocean, we adopt the following procedure. First, we create a viewshed image for a point located in the upper left hand corner of EADTMW and a point located in the upper right hand corner of the image. We then mask out the areas that are in the ocean. These land areas can be thought of as offering panoramic views of the ocean because the two viewpoints visualized from these areas are located wide apart in the ocean. The surface image for creating the viewshed will remain EADTMW. The viewpoint image, however, must be generated. We will follow the second procedure mentioned previously for generating these images.

Preparing the Data

i) Use the INITIAL module to create an image matching the row, column structure and pixel size of EADTMW and call it EAVIEW. Specify integer data type for the output image. We will use the UPDATE module from the Data Entry menu to convert EAVIEW to a viewpoint image. UPDATE first requires the name of the image to be updated. Specify EAVIEW as the image. UPDATE allows image cells to be updated as single cells, as horizontal or vertical lines of cells, or as rectangles of cells. Since we wish to create viewpoints, we are interested in the option of updating cells as single cells. In this case, the first and last row and the first and last column will be the same. For the first point, enter the value 1 to indicate that this cell holds a viewpoint. Specify the first and last row to be 0 and the first and last column to be 40 so as to select a cell in the upper-left region of the image. You are then asked for a value for this row and column. To update another cell for the second viewpoint, specify a value of 1 for the cell, 0 for the row and 205 for the column positions. Then click OK.

Creating the Viewshed

j) Now, run the module VIEWSHED and specify EADTMW as the surface image, EAVIEW as the viewpoint image, and PANVIEW as the output image. Choose a distance of 6550 meters (this approximates the distance of the diagonal from each viewpoint to its opposite corner) and a viewer height of 0 meters. The viewer in this case is the ocean viewpoints.

k) Next, use OVERLAY to multiply PANVIEW with MASK and call the output PAN. Display PAN with a 16 color palette. PAN shows all those areas on land that have a view of the point in the upper-left corner of the image and the point in the upper-right. We have simulated a panoramic view of the ocean. The land areas that have a panoramic view of the ocean have a value of 1 and those that do not have a panoramic view have a value of 0.

Part 3: Suitability Analysis

We have determined which areas of the coastal land have a panoramic view of the ocean. We now turn to an analysis of the other variables that may influence the development of the coastal landscape. In addition to the view of the ocean, our ability to enjoy the ocean depends upon the distance from the shore, the slope of the land, and the aspect (the angle at which a potential viewing area faces the ocean).

Creating Images of Development Criteria

Modules exist that will determine these variables from EADTMW. First, we will use the DISTANCE module to create an image showing distances on land from the shore. To run DISTANCE, it is necessary to have a feature image or a "target" which defines from where distance will be measured. Since we want distance to be measured from the shore, the ocean will be the target from which calculations are made.

l) Run RECLASS on EADTMW. Call the output OCEAN, and choose a user-defined reclass. Reclassify all ocean pixels from 0 to 1, and all land values (values greater than 0) to 0. Now, run the module DISTANCE and specify the feature image to be OCEAN, the "target" just created. Call the output EADIS. Look at the result and observe the range of data values.

m) Next we need to create the slope and aspect images. The SURFACE module automatically creates these for us from EADTMW as it is a digital elevation model. Run the module SURFACE from the GIS Analysis/Context Operators menu and choose the third option that will produce both images. EADTMW is the input image. Call the outputs EASLO (for the slope image) and EAASP (for the aspect image) and choose degrees as the output. Aspect is measured from 0 to 360 degrees clockwise from the north. Look at the results and visualize what the values in each image mean with Cursor Inquiry Mode.

3. Where slope is zero, what value is assigned to the aspect? Why is this so? What is the range of values possible of a slope to be facing south? (Hint: recall the direction the shore of the BASQUE region faces.)

In suitability analysis, different images are combined to produce a suitability map showing areas that are potentially useful for certain types of activities. In our case, suitability analysis can be used for predicting the development of the coastal landscape. In this example, we have four criteria for where development may occur:

1) only land areas with panoramic views of the ocean

2) with a north facing aspect

3) within close distance to the shore

4) with low slope

We therefore need to combine the different images to produce an image having land areas that meet the above requirements. This process is called suitability analysis. We met our first criterion by creating an image containing land surfaces with panoramic views.

To meet our next criterion, we limit the aspect image EAASP to contain only land surfaces facing north. It now contains aspects that range from 0 to 360 degrees. Slopes that face due south obviously are unlikely to have a view of the ocean. Thus, one wants only those slopes facing north that are within 60 degrees of due north (a slope of 90 degrees would be facing either east or west).

n) This can be done by reclassifying EAASP with the RECLASS module as follows: 1 = 0 - 61; 0 = 61 - 300; 1 = 300 - 361. Call the resulting image EAASP2. A simple OVERLAY/multiply operation between EAASP2 and PANVIEW will now produce those land areas with north-facing aspect. Multiply the two images together and call the result ASPVIEW. All the cells that have a panoramic view of the ocean and that have a north-facing aspect have a value 1.

The slope image EASLO also is not terribly useful on its own because it contains slopes for the entire land area of EADTMW whereas only slopes falling within the land areas having panoramic views of the ocean and with north-facing aspect are important.

o) Therefore, multiply EASLO with ASPVIEW in an OVERLAY operation and call the output SLOPE. Since this argument can also be extended to distances from the shore, also multiply EADIS with ASPVIEW and call the output DISTANCE. Note that some pixels have negative values in the result.

Next, we want to integrate the variables SLOPE and DISTANCE to produce the suitability map. However, with so many values in each image it would be difficult to interpret the output. We therefore need to reclassify each image to three levels.

p) For slope, use RECLASS to reclassify the image as follows: 1 = 0 - 10 degrees; 2 = 10 - 25 degrees; 3 = > 25 degrees. Call the reclassified image SLOPE2. For distance, reclassify the image so that: 1 = -236 - 300; 2 = 300 - 1000; 3 => 1000. Call the reclassified image DISTANCE2. (Note: We could have reclassified slope and distance images first and then multiplied them by ASPVIEW.)

Producing a Suitability Image

q) Finally, we will use CROSSTAB to combine SLOPE2 and DISTANCE2 to produce an image of the land areas that are suitable for coastal zone development. A cross-classification image will show where each category of slope occurs with each category of distance.

4. Why will multiplying the images not be useful?

r) Run the module CROSSTAB on SLOPE2 and DISTANCE2 and choose the option 1 for a cross-classification image. Call the result CROSSTAB.

5. What are the land areas within 300 meters of the shore, and have a slope between 10 and 25 degrees?

Summary

Depending on the management goals of the user, these levels could be classified or ranked in order of importance. There are many other ways to use these variables. For instance, we have integrated aspect only in one way to locate ideal views, but another planner may be particularly concerned about aspect in relation to sunshine. Someone concerned about the preservation of fragile ecological zones located on particularly steep slopes may desire a more detailed slope classification. A fishing community may prefer good views, but also may be concerned about the distances involved crossing to shore and returning back to a distributor or processor.

We are indebted to Francisco Heras and Juan J. Onate, Department of Geography, University College Cork, Ireland for making available the data and methodology used in this exercise.

References

Heras, F. and J.J. Onate (1991) "The Visual Influence of the Sea on the Landscape" obtained from Heras and Onate, Department of Geography, University College Cork.

Answers

Exercise 1: Fisheries Management

1. The coordinates are different.

2. The coordinate system of the raster files is UTM, zone 17. The coordinate system of the vector files is Florida State Plane. Before using this data, all files must be in the same coordinate system.

3. There are many possible sources of error in any procedure. Here errors may have been introduced by inaccuracy in depth measurement, digitizing, registration, or the inherent problems of interpolating unknown elevations (or depths) from a limited number of control points. While we can never be 100% confident about our results, ground truth measurements can help us limit the number of undetected errors.

4. While the orthographic projection cannot be used in any analysis, it lets us better visualize the area we are studying. With the HABITAT image draped over the bathymetric surface, it becomes clear that most of the seagrass areas are located in very shallow and protected waters.

5. The average depth for sparse seagrass is -1.844 feet, patchy seagrass is -1.978 feet, and dense seagrass is -1.094 feet.

6. Category 1 = 487.39 hectares, category 2 = 422.30 ha, and category 3 = 2115.27 ha. We could have run AREA on HABITAT and only examined areas for categories 4, 5, and 6.

7. The continuous data is more precise than is informationally useful. ASSIGN is not used because with continuous data it is a tedious, if not impossible, task to list every value that occurs in the image. This is particularly true when the data consist of decimal values that are better reclassified as ranges.

8. To mask the land, we first produce a Boolean image of land and water from HABITAT using either RECLASS or Edit/ASSIGN, whichever you prefer. In the new image, give the value 0 to the HABITAT category "undefined land" (in HABITAT undefined land has a value of 1) and give the value 1 to all other categories. Call the result TMPMASK. (If you didn't remember which category is "undefined land" you could use Metadata, choose HABITAT and click on the Legend tab to see the assigned values of the categories.) In RECLASS you would give a value of 0 to all values from 1 to just less then 2, a value of 1 to all values from 2 to just less than 999. Your Edit file would have looked like this:

1 0

2 1

3 1

4 1

5 1

6 1

9. (1507+13246+7963)/(1947+1687+8450) = 89.5% of the seagrass is in shallow water.

10.

MANGCATS Categories	Corresponding GRASBATH Categories
0	1
1	5
2	3, 4
3	7, 8, 9, 11, 12, 13
4	2, 6, 10

The most vulnerable seagrass area covers 1993.36 hectares. The total area of both vulnerable categories is 2707.55 ha. You might want to reclassify the depth image to 1, 2, and 3 foot depths to further subdivide the vulnerability levels for dense seagrass.

11. (4661/7963) = 58.5% of the most vulnerable management areas are shrimped.

12. The area for categories 6, 7, 8, 9, and 10 sums to 2542.58 hectares shrimped in Tampa Bay. If shrimping was eliminated in the vulnerable management areas, (1323.98/2542.58) = 52.1% of the areas now shrimped would remain.

Exercise 2: Mapping Seagrass

1. This is most likely due to a shadow being cast by buildings on the pier. The shadow shows up in the green band as an absence of reflectance (the shadow absorbs all light, including green). It does not show in the infrared band because all water (in shadow or not) absorbs infrared light.

2. If we had used the green band, there would have been no clear break in the histogram separating land reflectance from water.

3. The unsupervised classification has only partially isolated the seagrass bed. This is due to the change in reflectance (for any given bottom-type) which corresponds to a change in water depth. As the water gets deeper, it becomes more difficult to categorize seagrass areas.

4. The component one image probably does not correspond exactly to changes in depth for several reasons. However, one major reason is the failure of all three bands of input data to penetrate the water to the sea bottom. Separating variance due to water depth from other factors such as bottom-type will falter if only one of the bands is actually reflecting the sea bottom (in this case the green band). Ideally, all three bands should have short wavelengths.

Exercise 3: Bathymetric Modeling

1. No, neither the composite image nor any of the original bands can be used as an index to depth without some further processing. Other factors such as sea-bottom type and ocean surface scatter are contributing to reflectance value variance and these need to be accounted for before any imagery can be an index to depth.

2. Here, a mean filter works by replacing a given pixel's value with the average value of its neighbors. The IDRISI module FILTER passes a 3x3 matrix over each pixel and its 8 nearest neighbors. The average value of the 9 total pixels in the matrix is given to the center pixel. This filter will smooth the entire image by dampening the effect of both peaks and valleys.

3. The mean value of DEEPTM1 is 70.5646. The standard deviation is 0.9105. The estimated value of VS is 70.5646-1.0529 = 69.6541.

4. In TRANTM1 you can see changes in the reflectance values of off-shore pixels that appear to correspond to depth or perhaps to changes in sea-bottom types. This variation was not nearly as visible in the non-transformed imagery.

5. After regressing the values files TRANSTM1 and DEPTHS you get a slope = -12.9, a constant value = 45.3, and a correlation coefficient (r) = -0.72. Using these values and the equations in the text, we calculate *k* = 0.039 and *VO* = 33.6 (answers may vary due to rounding). Using this method, where we assume a simple linear relationship between the transformed radiances of the blue band and water depth, we need only to know the slope and constant values. Calculating *k* and *VO* are not necessary. However, they may be necessary in other more complex equations to calculate depth.

6. To make the image more map-like we could use HISTO to examine the distribution of values and RECLASS to reclassify the image into selected ranges of depth. The new image would have discrete categories corresponding to depth intervals.

7.

Site Number	Known Depths	Algorithm Depths	PCA Depths
		correlation coefficient *r*= -0.72	correlation coefficient *r*= -0.715
1.0000	2.0000	6.697	6.558
2.0000	6.0000	9.575	8.150
3.0000	6.1000	4.346	7.415
4.0000	8.2000	22.223	19.292
5.0000	11.0000	8.793	9.129
6.0000	11.1000	11.297	12.925
7.0000	13.5000	16.995	19.047
8.0000	13.7000	12.252	17.700
9.0000	17.2000	14.407	11.211
10.0000	22.7000	16.995	14.027
11.0000	19.7000	24.575	25.414
12.0000	27.6000	22.223	22.720
13.0000	33.8000	22.223	22.720

8. The mean value of FILTM2 = 18.2320, the standard deviation = 0.4452, and the estimated value for *VS* = 17.7868. The mean value for FILTM3 = 13.8178, the standard deviation = 0.4481, and *VS* = 13.3697.

9. Regressing the values files PCACMP1 and DEPTHS, we find the slope = -0.12439, the constant = 32.76, and the cor-

relation coefficient (*r*) = -0.715.

10. It is difficult to tell which is the best estimate of depth. Comparing estimations with just the thirteen available control points reveals discrepancies in both methods. PCA method appears to match our control points well in deep water, while the algorithm method works best in shallow water. Accurately rating either method would require further ground truth measurements.

Exercise 4: Coastal Change Detection

1. The real change in the coastal environment between 1985 and 1989 is difficult to determine because of the dominance of clouds in the 1989 image.

2. The most noticeable change event in the DIFF image is due to the clouds recorded in the 1989 image that are absent in the 1985 image. The change is therefore temporary because the clouds are not a permanent feature of the landscape.

3. The small peak at the right (high values) end of the histogram is caused by high reflectance values of the clouds.

4. Minimum = -197.00; Maximum =200.00; Mean = 9.87; and the Standard deviation = 41.81.

5. The values for reclassifying DIFF are:

Class 1 = from -197.00 to -73.75

Class 0 = from -73.75 to 93.49

Class 2 = from 93.49 to 201 (note that 201 is used rather than 200 because of the "just less than" upper limit of RECLASS)

6. Areas of significant change in CHANGE1 occur over the ocean surface while the zone of significant positive change occur over the coastal land areas. If the effects of clouds and cloud shadows are ignored, the ocean surface might still show a more significant negative change. This is because of the impact of tidal change which caused water level in the 1989 image to be higher than the level recorded in the 1985 image. The deeper water level in the 1989 image produced very low to zero values.

7. Summary statistics for DIFFMASK are:

Maximum = 47

Minimum = -188.00

Mean = -2.75

Standard deviation = 5.63

Note: Your values may differ from these because your WATERMASK2 image is different and will depend on the exact areas that were manually digitized. However, the mean and standard deviation values should be quite similar to these.

Because there are bright areas that are not clouds, you might not see the maximum value increase. However, removing the clouds should decrease the mean value significantly. The standard deviation should also be significantly smaller since the large number of high values lying far from the mean are now removed.

To see if the small histogram peak of high values has been removed, run HISTO with DIFFMASK. Use a class width of 1. Note that the mean and standard deviation values reported by HISTO are quite different than those found with EXTRACT because HISTO includes all the zero values in the masked-out land and cloud areas.

8. With the above statistics, the values used to create CHANGE2 would be:

Class 1 = -188 to -13.9

Class 0 = -13.9 to 8.38

Class 2 = 8.38 to 48

Your values will be slightly different. Remember to accommodate the "just less than" upper limit for class 2.

The CHANGE1 image is dominated by the positive changes caused by clouds. In CHANGE2, the positive and negative change areas are more balanced. The CHANGE2 image also shows more disaggregated areas of change than CHANGE1.

9. Areas of significant change delineated in CHANGE3MASK are quite similar to those in CHANGE2. More isolated pixels further from shore are shown in CHANGE3MASK.

10. The histogram distribution is highly skewed to the left. This is so because the values represent only the significant positive change direction. There are no negative values and all the values representing relative change in the image range from 0 to about 30.

11. Histogram of DISTQUERY

Class	Lower Limit	Upper Limit	Frequency	Prop.	Cum. Freq.	Cum. Prop.
-----	-----------	-----------	---------	------	----------	----------
0	0.0000	1.0000	1932	0.008	1932	0.008
1	1.0000	2.0000	30956	0.122	32888	0.130
2	2.0000	3.0000	43346	0.171	76234	0.301
3	3.0000	4.0000	49768	0.196	126002	0.497
4	4.0000	5.0000	36493	0.144	162495	0.641
5	5.0000	6.0000	30204	0.119	192699	0.760
6	6.0000	7.0000	18134	0.072	210833	0.831
7	7.0000	8.0000	13076	0.052	223909	0.883
8	8.0000	9.0000	8464	0.033	232373	0.916
9	9.0000	10.0000	5487	0.022	237860	0.938
10	10.0000	11.0000	3381	0.013	241241	0.951
11	11.0000	12.0000	2195	0.009	243436	0.960
12	12.0000	13.0000	1474	0.006	244910	0.966
13	13.0000	14.0000	1182	0.005	246092	0.970
14	14.0000	15.0000	873	0.003	246965	0.974

About 5% of the values in the image are above 11.00 in this case. Your answer may vary because your WATERMASK image may be slightly different.

12. Most of the significant change areas occur over the sea. The image differs from those produced earlier with other techniques because instead of aggregate change, it deals with relative change direction between the images for both 1985 and 1989.

13. There is only one category that has combinations of category 0 in any images because only the masked areas have value 0 and the same mask was used to create all three images.

14.

	B	G	R
1	mask	mask	mask
2	-	-	-
3	+	-	-
4	-	+	-
5	+	+	-
6	-	-	+
7	+	-	+
8	-	+	+
9	+	+	+

15. The change directions of interest are represented by categories 9 and 5. Category 9 has by far the highest frequency in the significant distance areas. However, the category 9 areas may be dominated by cloud shadows. Categories 2 and 5 have the next highest frequencies. There are many ways to find this answer. One way is to multiply CHANGEDIR and CHANGEDIST2 (the Boolean significant change distance image) then use HISTO with the result. If you set the minimum value to 1 rather than 0 it is easy to see the differences in frequency for the different change direction categories.

Exercise 5: Monitoring Erosion

1. The greatest density of real data points were collected near or onshore. The horizontal lines are the profiles along which the offshore depth measurements were taken.

2. Near and onshore areas in this surface image are very smooth due to the large number of data points originally. However, offshore areas look less smooth because of the spacing of the original data.

3. Now that the image is a continuous surface, the histogram reflects the fact that there are simply more data points. The histogram is not smoother because the surface was not interpolated; frequencies are simply higher. The dip in the histogram could be the result of the sampling scheme. Because the surface was not interpolated, a dip in the profile data should manifest itself as a dip in the continuous surface.

4. At present, elevation values are referenced both above and below mean sea level. In order for us to calculate volume, we will first have to transform change from mean sea level to height above an arbitrary base. It does not matter what base value we use because we are only interested in change in volume from one year to the next.

Total Volumes	Differences	Total Difference
1985: 28,006,213		
	85-89: -376,318	
1989: 27,629,895		
	89-90: +302,005	85-91: +107,977

Total Volumes	Differences	Total Difference
1990: 27,931,900		
	90-91: +182,290	
1991: 28,114,190		

5. Our initial hypothesis as well as the way we look at the data need to be modified. While we know that erosion is a problem along this beach, we do not know where and to what degree. The total figures cannot tell us if erosion and deposition are happening unevenly throughout the study area. Also, the sand replenishment program may have effected our net sand numbers.

6. Reclassifying all areas above 25000 square meters to equal 1 would be a mistake because the background area would be included.

7. Knowing the years that the sand was dumped on the beach (1989-90) and the dump locations (the small circled areas in the vector file LINES) we can assume that the dumping of sand partially explains the pattern of erosion. All areas were eroding previous to the sand dumping program. During the years of dumping, the southern spots show an increase in sand while the northern spots stabilize (perhaps due to sand drifting north). In the years after the dumping, severe erosion resumes in the locations to the south.

8. 379 m^3 of sand will be needed to replace the sand lost from Group 2 between 1985 and 1991.

Exercise 6: Modeling Sea Level Rise

1. Choose a new value of zero for values from 0 to just less than 1.9 and a value of one for values from 1.9 to 999.

2. Group number two represents the ocean area.

3. The area flooded due to the sea level rise is 284.6 hectares.

4.

1 - 7.1 ha	2 - 100.9 ha	4 - 88.2 ha
5 - 1.8 ha	6 - 45.2 ha	7 - 23.3 ha
8 - 3.6 ha	12 - 7.0 ha	14 - 7.4 ha

All other categories are zero.

5. Category zero has the value 100% because the same area is calculated for category zero in FLDAREA and LNDAREA. This yields a ratio of one for that category, and a percentage of 100. The Wetlands category contributes the most to the flooded area with 35.5%.

6. Use AREA to make an area image of RILANDU, then use OVERLAY to divide the area image for landuses in the flooded area (LNDAREA) by the area image for landuses in the entire study area. Use SCALAR to multiply that result by 100 to produce percentages. Use EXTRACT with the minimum option with the image of landuses in the flooded area (FLOODLND) to see the tabular results.

1 - 3.4%	2 - 5.3%	4 - 3.6%	5 - 2.2%
6 - 46%	7 - 2.0%	8 - 0.5%	12 - 0.4%
14 - 3.0%	All other categories are zero.		

7. To make the new DEM, subtract 1.9 from RIDEM, then reclass the negative values to zero. This may be accomplished with various combinations of SCALAR (or INITIAL and OVERLAY) and RECLASS. For example, use SCALAR to subtract 1.9 from RIDEM, then use RECLASS to change all negative values to zero. To make the new landuse map, the flooded areas must be given the landuse category number 0. This may be accomplished with OVERLAY, multiplying LAND2100 by RILAND.

8. Accounting for error and using a 75% probability, the land area is 7781 ha and the ocean area is 3891 ha. This compares to 8214 ha and 3459 ha respectively, as calculated by running AREA on the image LAND2100, created in Part 1.

9. Because all the pixels of RIDEM that are below sea level have been assigned the value zero rather than their actual negative elevation values, PCLASS cannot assign true probability values to these pixels. Only those pixels that have actual elevations of zero and above can be accurately assigned probability values. Clearly a pixel near the deepest part of the ocean area has a much smaller chance of having an actual value above sea level than does a pixel very near the shore, yet without bathymetric data, both of these pixels will be assigned the same probability values.

Exercise 7: Aquaculture Suitability

1. Mangroves, 3%; Forest, 35%; Grasslands, 35%; and Agriculture, 2%.

2. Yes. Suitable areas in SUITABL3 are approximately 77.8% of the size of suitable areas in SUITABL2. This is found by calculating areas for category 1 in each image using the AREA module and dividing the one by the other.

3. 1 = 3372.48 ha, 2 = 3490.56, and 3 = 17647.20. Use GROUP, AREA, and RECLASS to create an image of all areas > 5 ha.

4. The advantage of using the CROSSTAB module is all possible combinations of land cover and suitability are calculated. This can be used with AREA to calculate the extent of each combination. One potential disadvantage is that the resulting cross-classification may yield so many categories that it becomes visually difficult to interpret.

5. OVERLAY multiply TMPGRP1 times the Boolean image MANGROVE. This will produce an image in which all non-mangrove areas have a value of 0.

6. Areas of fewer square hectares than 50 do not represent feasible aquaculture zones. The last significant group is 2630 hectares. It is necessary to reclassify the background to 0.

7. Running AREA on the images reveal that they are not significant in terms of the total area changed. However, the additional pixels play an important role in giving a more accurate measure of shoreline complexity.

8. Enter a buffer width of 170 and a target area of 0.

9. Run EXTRACT using ALLMG as the feature definition file and COMPLEX as the image file to process. The resulting shoreline complexity values are:

1	2
2	1
3	1
4	3
5	3
6	3
7	3
8	2

9	3
10	2
11	2
12	3
13	1
14	2

Run AREA on COMPLEX to get the total area for each category. Most complex = 1611.36 ha, Complex = 1484.64, and Least complex = 9911.52.

10. Area available = 5217 hectares. The distribution of these suitable areas appears relatively diffuse.

11. The breakdown of land categories which comprise the suitability zone: Rangeland = 1715 ha; Pasture = 623; Agricultural = 619; and Dec. forest = 2233. Of the total area in SEMINTEN, almost half of it is deciduous forest, and therefore not as suitable for semi-intensive shrimp aquaculture.

12. Relative frictions for each category are:

2	0.120
3	0.205
4	0.205
5	0.480
6	0.480
10	0.900

13. One possible method to calculate the effect of the "dry weather only" category is to calculate the average probability of that particular road being wet. If we assume that at a given period of time the probability of rain is 30% (This is not empirically true of the Nicoya region, but the concept would hold if we knew the probability), we can reduce the expected speed on the dry weather road by 30% from 15 k.p.h. to approximately 10.4 k.p.h, changing the friction value to .692 for category 6.

Exercise 8: Coastal Development

1. Masking out land pixels will provide the answer. Create a mask image in which land = 1 and sea = 0. To make the mask, reclassify all EADTMW elevations above 0 to 1. Multiply the resulting image with the view image in which in-view = 1 and not-in-view = 0. Multiplication yields the following result:

1	x	1	=	1
1	x	0	=	0
0	x	1	=	0
0	x	0	=	0

When both conditions are met -- on-land and in-view -- the resulting image will have values of 1. All other possible combinations of conditions will have a value of 0.

2. When the mask image and view image are added together, the desired area takes on a value of 2 and all other combinations take on a value of 1 or 0.

1	+	1	=	2
1	+	0	=	1
0	+	1	=	1
0	+	0	=	0

3. When slope is zero, aspect is assigned a -1. South-facing slopes are those between 90 and 270 degrees.

4. We want to view all possible combination of categories. By multiplying the two images, we would not know, for example, what the value 6 meant in the result because 6 can be generated in two ways: either category 2 in SLOPE2 and category 3 in DISTANCE2 or category 3 in SLOPE2 and category 2 in DISTANCE2.

5. If SLOPE2 is the first image in the cross-tabulation and DISTANCE2 the second, then the category with a combination of categories 2:1 meets our criteria of slopes within 10-25 degrees and distance <300m from shore.