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Developments in remote sensing, dynamic modelling and GIS applications for integrated coastal zone management

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Abstract. The International Institute for Aerospace Survey and Earth Sciences (ITC) has a research programme that should result in an integrated environmental coastal zone management system through three subprojects. The programme aims to develop methodologies and tools for assessing coastal zone changes, and for the evaluation of scenarios for coastal zone management, based on a spatio-temporal Geographical Information System (GIS) working platform which integrates remote sensing data, physical-morphodynamic and eco-hydrologic modelling, and a decision support system.

The first subproject develops methodologies for the generation of optimum Remote Sensing (RS) data sets, leading to better interpretation and complementary use of conventional and new remote sensing imagery. It also integrates RS, GIS, and modelling through hypothesis generation, parameter estimation, evaluation and validation.

The second subproject facilitates qualitative and quantitative analysis and prediction of the physical aspects of coastal landscape development under the influence of natural processes and human impacts. This subproject is based on the application of remote sensing and dynamic modelling.

The third subproject leads to a spatio-temporal working platform which supports data integration of RS and in-situ measurements, and qualitative and quantitative analysis for the prediction of coastal landscape development. Both support decision making in Integrated Coastal Zone Management.

Keywords: Decision Support System; Image Analysis; Morphodynamic modelling; Remote Sensing.

Abbreviations: RS =Remote Sensing; MBIA =Model Based Image Analysis; GIS =Geographic Information System(s); DSS =Decision Support System;

Introduction

The research programme described in this paper demonstrates the interrelationships between physical and ecological processes, using Remote Sensing (RS), modelling and GIS techniques. It integrates and improves the technologies that are available but have not yet been fully exploited. The expected results include the development of methodologies and tools to assess the hazard and risk vulnerability in the coastal zone in space and time, to define the environmental indicators and indices on which the decision-making process can be based, and to evaluate coastal zone management strategies.

Remote sensing techniques

The growing concentration of population and socio-economic activities in coastal zones increases the pressure on coastal systems, which at the same time are threatened by various natural hazards, including the generally assumed sea-level rise. In order to support the development process and to minimize the loss from possible disasters in these areas, it is necessary to monitor and to assess the ongoing coastal processes and developments and their consequences for the systems through effective and efficient (environmental) management.

Effective and efficient management depends on the availability of sufficient, proper and timely information for thorough analysis. Due to the rapid and large-scale access to multi-platform, multi-spectral, multi-resolution and multi-temporal information, RS is used for data collection in many coastal areas. In this context, there are three main elements for which RS may play a role:
¥ providing information on marine and coastal properties;
¥ providing baseline information on the coastal environment;
¥d etecting, mapping and measuring of e.g. sea state, pollution, sediment transport, and coastline changes.

RS techniques generate different kinds of imagery with specific characteristics and applications. Aerial photographs have a high spatial resolution and thus they are suitable for detection of phenomena in a form similar to the human eyeÕs view. Landsat TM and SPOT satellite sensors detect objects in the (visible) light and infrared bands. They can produce natural- and false-colour images, carrying additional spectral information with high reliability on e.g. the water surface and water quality differences, vegetation types and the differences of biomass and vitality of vegetation. An overall view of the (tidal) sea surface changes is not feasible with aerial photographs. The time for image acquisition is longer than the changes in the environment. Satellite imagery does not have that drawback, but the repetition period and the moment for observation are too limited for adequate monitoring of the sea state and sequential and homogeneous condition analysis. The solid-state Charge-Coupled Device (CCD) imaging sensors have greater radiometric resolution than either photographic film or vidicon cameras and can be obtained under less favourable flight conditions. Hence, they may be specially suitable for sequential monitoring of dynamic changes within short time intervals, e.g. tidal changes.

Under cloudy weather conditions RS techniques, using the visual and infrared spectral bands, might fail to catch sufficient information if there are clouds obscuring the coastal area. All-weather microwave sensed imagery, e.g. Synthetic Aperture Radar (SAR) imagery, has hardly any constraint imposed by clouds, and is potentially suitable for mapping and monitoring changes of waves, tides and currents. SAR interferometry and laser altimetry can be applied to update and monitor land subsidence, accumulation or erosion. However, the resulting SAR images and laser relief profiles are quite different from aerial photographs and (natural) colour satellite images. New interpretation concepts and tools are required.

The same is true for the new laser remote sensing technique LIDAR (Light Detection And Ranging). Due to its high spatial and height resolution as a result of the angle and radiometry of the LIDAR beams, it has shown its value in providing accurate relief profiles as well as reliable wind speed and wave data, useful for monitoring and assessment of climate and pollution. Imaging LIDAR may also deliver useful additional spatio-temporal information, particularly for wetlands. With the help of Global Positioning Systems (GPS) for locating position during flying, radar and laser altimetry can be used to obtain terrain elevation data for generating and / or updating Digital Elevation Models (DEMs) quicker than traditional photogrammetry. Acoustic sounding (SONAR) can be used as a complementary tool to Synthetic Aperture Radar (SAR) and laser-altimetry for bathymetric surveying when the sea bottom topography is too complex and/or too time consuming to be measured by other surveying equipment and techniques.

The above discussion briefly illustrates advantages and disadvantages of some RS techniques. The impression is that there is great potential for obtaining better or additional data sets through a series of new remote sensing techniques, such as SAR imagery and interferometry, imaging LIDAR, CCD videography and acoustic sounding to supplement conventional (visible and infrared) aerial photography and satellite imagery. The experiences of the last decades in the attempt to develop advanced multi-sensor, multi-spectral, multi-source image fusion systems (Pohl 1996) might be a starting point for new research focusing on Model Based Image Analysis (MBIA). MBIA is a method which results in the optimum potential of RS data by integrating RS and GIS through hypothesis generation and evaluation and by parameter estimation (see Section 1). Then there will be data assimilation of remotely sensed information, in-situ measurements and the results of numerical models, which will broaden the potential of remote sensing.

Modelling

The integration of RS data and dynamic models in a spatio-temporal GIS can contribute to quantitative morphodynamic prediction of the coastal zone in relation to e.g. coastline defence and landscape development. Then, decision-making will be facilitated and management alternatives can be presented. However, knowledge of the processes, the interactions of these processes and the governing factors concerning e.g. the sediment balance and transport on the land-sea interface is needed to be able to predict which physical, morphodynamic and eco-hydrologic processes will dominate in the future at a certain location and what will be the consequences thereof.

GIS working platform

In order to support the management of multi-source information and (morphodynamic and eco-hydrological) modelling, a spatio-dynamic representation of the coastal changes is necessary. However, most of the existing GISÕs have a two or two-and-half dimensional operation system. Thus they can represent and analyse natural phenomena in only those spatial representations. The GISÕs that can support a so-called two and half dimensional operation, such as Digital Terrain Modelling, cannot capture and visualize information under the terrain surface or changes along the vertical profile. Also the time factor is not explicitly included in these systems. Therefore, they cannot carry out adequately dynamic analysis, support simulation of the past, or represent the present and predicted conditions in the future; aspects which are important for coastal zone studies and management. A spatio-temporal GIS (three spatial dimensions and one temporal dimension) seems to be the ideal tool to represent and to analyse the spatial and temporal phenomena of the coastal zones.

GIS-based decision support system

For the management and monitoring of coastal resources for sustainable development, a GIS-based Decision Support System (DSS) is most useful. It facilitates efficient strategies based on data integration, data analysis and modelling, assessing the impacts derived from anthropogenic activities, modelling of natural processes, predictive simulations and legislation assessment. Such a DSS should consider among others:

¥ dynamic environments;
¥ accuracy needed for representing coastal features and processes;
¥ coastal hazards and risks;
¥ alternative activities of land use, protection or expansion of coastal areas;
¥ sensitivity analysis, critical in a dynamic situation;
¥ normalization techniques for spatial- and time-dependent data (e.g. for indicators of change, such as acceleration of processes);
¥ pressure of industry and tourism;
¥ seasonal activity (e.g. greater vegetation and tourist density in summer).

Description of the subprojects

The following sections will indicate how research in the three subprojects is directed to fulfil the expectations.

Subproject 1: Model based image analysis for use of remote sensing in integrated coastal zone management

The need for model based image analysis (MBIA)

Most problems in visual and computer-assisted analysis of remote sensing data are related to insufficient representation of knowledge. MBIA is an attempt to promote the disciplines involved (e.g. oceanography, geomorphology or ecology) with the extraction of information from digital remotely sensed imagery on a more scientific basis, governed by facts, and constrained by natural and physical laws. The method of MBIA functions through knowledge-based image analysis in which the physics of objects and remote sensing will be represented by numerical models (Mulder 1994). This contrasts with the representation of empirical, context-dependent knowledge often represented by qualitative rules. The MBIA method is based on predictive models, and can predict the RS image properties from object and process models combined with remote sensing models through sensor measurements from the object (images) and sensor parameters. To make this possible, advanced numerical techniques are to be applied to extract the most likely parameter values by model inversion.

The method under development is based on the assumption that both object parameters and sensor/sensing parameters can be retrieved from (multiple) sensor measurements, given that sufficient prior knowledge is available and that through independent ground observations it can be verified. Then subjective picture manipulation procedures can be avoided, while the analysis system works directly towards the goals set by the information requirements, which in turn depend directly on the decision-making model.

The integral use of such a model in a spatio-temporal GIS is under investigation, particularly for new and promising techniques such as SAR interferometric data, airborne CCD video data, 35 mm digitized (KODAK CD) images and LIDAR.

MBIA in coastal zone environmental management

The integration of RS data and GIS technologies is frequently based on modelling and simulation characterized by the ÔartÕ of putting image transformation in sequence according to a recipe or by trial and error. With large volumes of available RS data and little specific knowledge about the objects and processes, the data-driven approaches are likely to succeed in estimating the state of the environment in an empirical and operational manner. However, integration must have a predictive power with sufficient knowledge about all of the systemÕs components, i.e. the scene (field/image) and the sensing and imaging processes. Here, the integration of RS and GIS should be achieved through hypothesis generation and evaluation/validation and by parameter estimation (Mulder 1994). An iterative procedure may adjust the hypotheses and the parameters on the basis of the costs of errors in predicting the RS measurements. In this GIS-based system, the scene model may result in improved RS imagery defining the objects with a specific accuracy, provided either in terms of likelihood or in terms of integration of minimum risk values for the hypothesis and parameters.

Fig. 1 shows the MBIA method by which a hypothesis of a sensor and object model has been predicted from the observed and measured data for a certain initial set of parameters, compared with the actual measured data using a cost function which evaluates the usefulness of the image. The cost function is based on the differences between predicted data (hypothesis) and measured data (observation); the estimated cost of error (the difference in the actual and the optimum estimated image) can be calculated:

$$Cost = (m \text{ Ð} h)^2 \quad (1)$$

where m = the measurement; h = the hypothesis/predicted measurements (parameters).

From the flow diagram of Fig. 1 it can be observed that the optimizer (estimator) keeps changing the parameters of the sensor/sensing model and the object model until no lower cost can be found. The idea of this iteration loop is to define the best set of parameters which, together with a sensor/sensing model and an object model, describes the best solution (Schutte 1994).

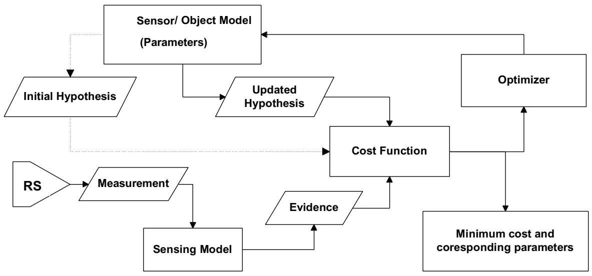

Fig. 1. Model based image analysis (MBIA) using minimum cost estimation of a hypothesis and corresponding parameters.

We suppose that this MBIA method is applicable for coastal zone management and facilitates a workable Spatial Information and Decision Support System (SIDSS).

Remarks

The integrated use of multi-sensor RS data, based on the MBIA technique, should result in the definition of the best set of parameters which describes the best solution for obtaining the most reliable data sets for coastal studies. This will be the case if it is possible to:

¥ define the role of multi-sensor remote sensing image analysis in the definition of minimum risk for a specific information user;

¥ establish the sensor and platform parameters and a sensing model under assumed a-priori likely hypotheses and parameters Ð which leads to two important geo-informatic problems:

- object parameter estimation given one sensor and a multiple view data set, and
- object parameter estimation given various and different sensors;

¥ evaluate and validate the hypotheses, and to estimate the best parameters;

¥ represent the residual uncertainty in the model;

¥ update the state models based on image analysis results.

Subproject 2: Integration of dynamic models and remote sensing monitoring techniques in a spatio-temporal GIS for integrated coastal zone management

Predicting morphodynamics

The research programme should find a method for qualitative and quantitative prediction of the morphological development of a coastal landscape under influence of natural processes and human impacts, based on suitable RS data and the application of dynamic modelling and GIS techniques. The method will be tested for the morphodynamics of the sandy coast of the Dutch coastal barrier island Ameland, at time scales from several months to several years. Subsequent attention can then be paid to the consequences of the morphological predictions for coastline defence *i.a.*, but, to some extent, also to the hydrological and ecological development of the dunes. Insight into both the morphodynamic and eco-hydrological processes can serve as a basis for management.

The study of coastal changes during the recent past (5-10 yrs) and present forms the basis for prediction of the morphology in the near future. It can benefit from the increased frequency of data generation through air- and space-borne RS techniques. The prediction of the future morphology has to be in the order of years as well. Upscaling in coastal morphodynamics is very difficult, since these may be the result of complex, and possibly chaotic, processes and interactions in the coastal zone. Thus, trends on a lower scale may be considered as noise on a higher scale level.

On the other hand, large-scale fluctuations sometimes seem to influence the results of smaller-scale morphodynamic predictions significantly. This may include large-scale transport processes, e.g. as a result of the migration of Ôsand wavesÕ on the foreshore, or the impacts of climate change. For the prediction of morphodynamics at a certain scale one should have knowledge on processes acting on a larger time scale. Fig. 2 shows the theoretical concepts of the different levels of coastal behaviour within coastal geomorphic systems.

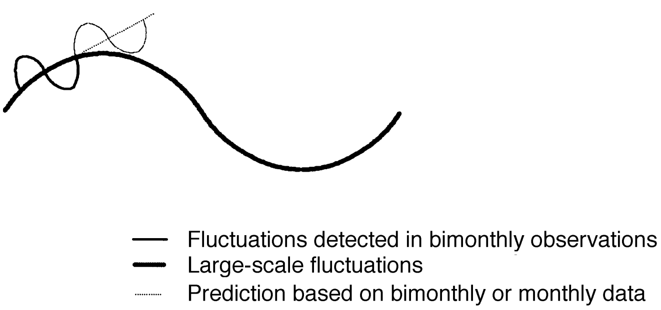

Fig. 2. Large-scale sand transport and climate change fluctuations influence prediction of morphodynamic phenomena at a smaller scale (after Terwindt & Kroon 1993).

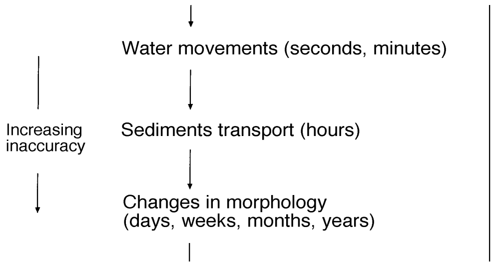

Fig. 3. Increasing inaccuracy with increasing time scale of the process modelled (after Kroon 1994).

Qualitative morphodynamic prediction

RS techniques are complementary to non-RS-data, (e.g. ground-truth data) and may each have practical advantages for analysis, mapping and monitoring of certain landscape aspects within the active landscape units. RS images are to be analysed and classified with image processing techniques, leading to a qualitative prediction of near future development. This prediction is feasible because RS data allow us to define qualitative empirical relationships that describe the exchange of sediment volumes in the research area.

Quantitative morphodynamic prediction

To enable quantitative monitoring and prediction of changes, information from the RS data will be used for morphodynamic modelling. The results from the above-mentioned empirical qualitative research can be used additionally for calibration and optimization of the parameters of the models. The present generation of morphodynamic models is divided into two main categories, depending on the concepts for describing the actual processes within the system and the resulting output, i.e. the process-related models and the behaviour-related models.

Models that are based on a detailed description of elementary physics of the fluid and the sediment particle motion are classified as process-related models. The use of these models requires a detailed knowledge of the physics of many interacting processes (Hoekstra 1995). Current research in the framework of a project on innovative nourishment techniques shows that quantitative morphodynamic predictions from process-related models often do not correspond with reality (A. Kroon pers. comm.) because of the stochastic character of the morphodynamics of coastal systems, and the increasing inaccuracy with scale (Fig. 3). This type of modelling, however, does provide much insight into the processes and can therefore be used as extra information for qualitative prediction. In this context the use of a new model for uniform beach sediment transport (P. Hoekstra pers. comm.) could be considered for the research.

In behaviour-related models, the physics are only included at a high level of abstraction; i.e. the physical details are no longer incorporated in those models. In this way, the morphological development of large-scale coastal features is represented by relatively simple algorithms, combining both process-related information (e.g. from stripped process-based models) and empirical data sets, showing the development based on observations in the field or on RS images (Hoekstra 1995). These models seem to be more suitable for quantitative prediction and integration in a spatio-temporal GIS. However, the possibilities for adaptation and consequent integration of existing models depend on the qualitative empirical relations between sand sharing systems and the level of coastal behaviour described in these models.

For the study of the Ameland coast, of which morphologic changes are considered on a time scale of months or years, and of which the data set mainly consists of RS data and of yearly elevation data along various transects (the so-called JARKUS data, de Ruig & Louisse 1991), a full integration of models in GIS, through development of new models within a prototype spatio-temporal GIS environment (see next subproject), might be the most convenient solution (Cremers et al. 1995; Goodchild et al. 1993). Fig. 4 shows the proposed approach to be taken in modelling morphodynamics.

Identification of management scenarios

With the knowledge of processes and interactions of sediment transport on the land-sea interface and predictions of the volumetric changes, it will be possible to design scenarios of future changes and predict their environmental consequences. With an additional input of data on current and possible management practices, alternative possibilities for management can be tested and presented through the identification of future management scenarios. In this way management activities for coastal defence which require high investments, such as beach nourishment or the planting of marram grass (*Ammophila arenaria*), can be optimized.

The procedure is illustrated in Fig. 5. The results of the different phases of research and the different objectives are mentioned in the boxes.

Remarks

Research on RS and dynamic modelling of coastal zones can benefit from the following new developments in various disciplines:

¥More (diverse) and useful RS data are becoming available, facilitating the extraction of information that can be used in models.

¥ In the past, morphodynamic research was mainly descriptive but now the Ôsystems approachÕ is adopted. A study area is seen as a system with strongly interdependent

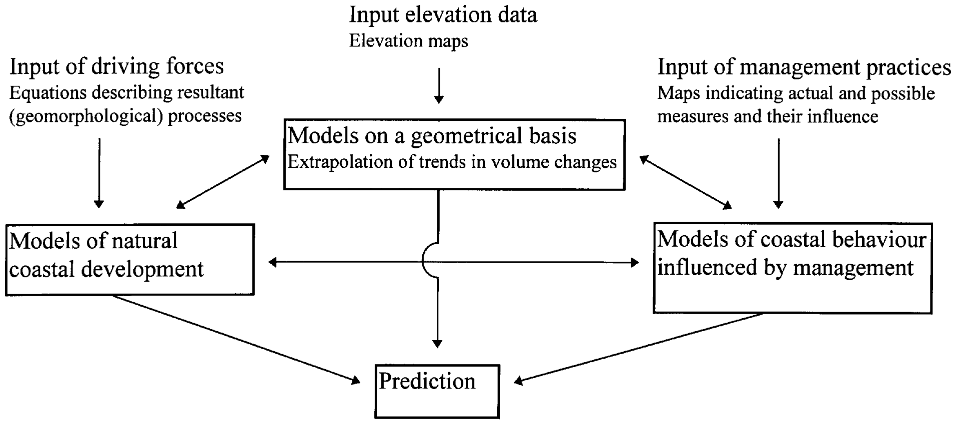

Fig. 4. Modelling coastal behaviour in a spatio-temporal GIS environment.

sub-environments or landscape units, sharing an amount of sediment. Processes, like marine or aeolian sediment transport, present interrelationships between the various landscape units (Oost & de Boer 1994; Hoekstra 1995). Therefore, the development of Ôobject-oriented programmingÕ can be an impulse for modelling morphodynamics, as it supports the simulation of the system with subsystems and interrelations (Cremers et al. 1995).

¥Many models that can be applied in the coastal zone have become available; these models are two dimensional (2-D) horizontal, 2-D vertical, 3-D and even 4-D (Cremers et al. 1995). In the last few years, progress has been made in the parameterization of coastal behaviour and in the development of behaviour-oriented models (Terwindt & Kroon 1993; Kroon 1994; de Vriend et al. 1993).

¥The possibilities of integrating dynamic models with GIS are being investigated in several research institutes. Successful examples of loose coupling and of full integration of the model in a GIS have been reported (Cremers et al. 1995; Goodchild et al. 1993). A first attempt has been made to develop a practical tool in a dynamic modelling language, which allows direct modelling in a GIS environment (Wesseling et al. 1996).

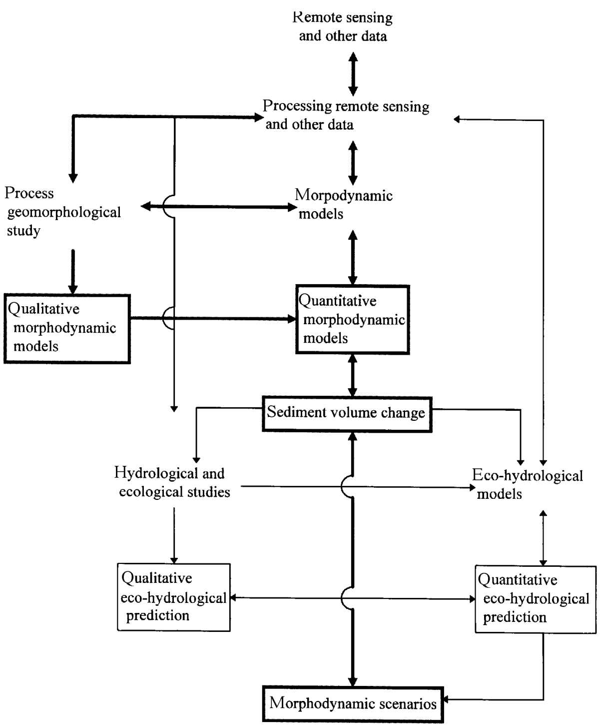

Fig. 5. A method for the application of RS in dynamic modelling and for decision support in sustainable development of coastal zones.

Development of a spatio-temporal GIS shell to support coastal environmental modelling

The need for a spatio-temporal GIS shell

Natural phenomena show large spatial and temporal variability. Coppock (1995) stated, that Ònatural phenomena are multidimensional and multi-disciplinary phenomena which, whatever their initial focus, have a strong spatial component. Understanding and coping with them requires access to spatially-referenced data from a wide variety of sources, at different scales, resolution and reliability, and often over time, and imply analyses of such data in four dimensionsÓ. The horizontally and vertically varying distribution of moving water and sediment is an example of such a complex spatial and temporal variability example. To understand and simulate the formations, changes and interactions of this variability, dynamic representing, analysis and modelling of these phenomena are necessary. In our test area, research of geomorphology of the coastal dunes is required to reveal the temporal and spatial dynamics of their mobile nature and their interaction with beach processes. A complex computer system, GIS is used to collect, store, retrieve, analyse, query and display geo-referenced data. All these functions can be used to facilitate environmental modelling. Particularly spatio-temporal GIS facilitate better access to data, efficient data processing and diverse output capabilities which Òlead to immediate evaluation of data quality and model results, thus enabling rapid improvements to the spatial form of the data and its modellingÓ (Batty & Xie 1994).

As mentioned before, most (commercial) GIS are two or two and half dimensional (2-D or 2.5-D). They can assemble a variety of data to produce static maps and to show how natural phenomena vary spatially. None of them includes the temporal dimension. Consequently, they cannot support time series information and dynamic analysis. As for environmental modelling, only simple deterministic models can be developed or integrated in most current commercial GIS. The lack of a time factor in GIS results in drawbacks of GIS application for environmental studies (Coppock 1995; Burrough 1996), for example, in the application of GIS to coastal natural hazard mitigation, where models should deal with varying and complex circumstances.

In this context, Mason et al. (1994) stated, that Òthere seems no overriding reason why GIS should not be developed to assist in complex environment modelling, in a way that involves close integration of the GIS and the modelÓ. It implies that a new generation of GIS including the time dimension is required to support environmental modelling. Only a spatio-temporal GIS will provide the means to understand, explain and predict future events (Al-Taha & Frank 1993).

Spatio-temporal data models

At present, four basic conceptual spatio-temporal data models are available, i.e. the Space-Time Cube (ST-Cube), the Snapshot, the Space-Time Composites (ST-Composites), and the Spatial-Temporal Objects (ST-Objects) models. The ST-Cube model is a 3-D cube representing one time dimension and two spatial dimensions. It depicts processes in a 2-D space which act along a third time dimension (Langran 1992). Snapshot models are images with a geographic distribution at different times, just like remote sensing images of an area taken at different times (Armstrong 1988). ST-Composites represent objects, of which the boundaries have sharp attribute changes (Langran & Chrisman 1988). The ST-object models are seen as a finite collection of disjointed prisms (ST-atoms), where S is the base of the prism, representing its spatial extent, and T is the height of the prism, representing its temporal extent (Worboys 1992, 1994).

Recently, the ST-Cube model has been extended to a 4-D space, i.e. a 4-D hyper-cube built by bitrees (Mason et al. 1994). Such a 4-D hyper-cube model might facilitate the interpolation along the four dimensions, but extraction and tracking of the objects is quite difficult. Spatio-temporal object concepts can now be used in a 4-D geomorphologic information system, i.e. OOgeomorph (Raper & Livingstone 1995). The OOgeomorph system can handle point-based locational information well, but has difficulties in manipulating area data and topological relationships (Yuan 1996).

Other concepts that might have a future for handling spatio-temporal objects are the Triad Model (Peuquet 1995; Peuquet & Qian 1996) and the Three Domain Model (Yuan & Albrecht 1995). The triad model shows three views of spatio-temporal changes as feature-based, event-based and location-based changes. The feature-based representation includes the generalized locational indicator, temporal intervals, non-spatio-temporal data and the class type of the feature. In the event-based model, an event is stored as an observation in the time-based view. Each event and attribute described is stored in its chronological order of occurrence. The location-based representation is a raster-based snapshot. Although it seems a great step forward in handling spatio-temporal data, the question of complexity of the querying process is not fully answered (Roshannejad 1996).

Each of the existing spatio-temporal data models (STDM) has its pros and cons. It seems that they do not represent the way the object is changed from one state to another. In other words, the processes underlying all dynamic changes are not explicitly and adequately represented in the spatio-temporal data. Therefore, we propose a process-oriented spatio-temporal data model, which presents the changes of natural phenomena in a set of dynamic processes (move, transfer, erode, etc.) explicitly represented in the data model and fully embedded in a spatio-temporal GIS. Then the features can be represented in an initial state with the developing processes.

A process-oriented spatio-temporal data model

For studies of the natural environment, two models can be used to capture the important aspects of physical phenomena: the field-oriented model and the object-oriented model (Goodchild et al. 1993; Kemp 1992; Burrough 1996; Molenaar 1995). In the field-oriented model the environment is continuous. Each attribute is assumed to vary continuously and smoothly in space. It is a locational-dependent representation in the sense of Ôwhat exists whereÕ, i.e. the thematic information of the entities is attached with their locations or geometric data. In practice, the ÔfieldÕ is often discretized to a regular grid at a given level of resolution within a GIS. In the object-oriented representation, the world is made up of objects with crisp spatial boundaries and a well defined set of attributes, which are linked together through the unique identifier of each object. The data are structured in the GIS according to the object, describing Ôwhere it is and what thematic attributes it hasÕ.

It seems that both the object and the field concept are not sufficient to describe the natural phenomena. To capture these two aspects in a GIS, environmental modelling needs the object concept, whereas its spatial distribution is continuous. Therefore we propose the ÔfeatureÕ model, which represents the real entities used in the specific field of application. This model reflects a particular application context and resolution of the representation (such as pollution plumes with fronts and effuse in oceanography and meteorology). Here, a feature is categorized as an abstract representation of a natural phenomenon (such as a coastline, dune or beach) and defined according to the application discipline. Its boundary is created by applying categorizing rules to discretize the reality. The interior or volume of the feature still has field-oriented properties, representing the natural phenomenonÕs gradual and continuous distribution perspective. In our test area Ameland, the landscape units foreshore, beach and foredune are considered as such kind of features.

Claramunt & Therlault (1996) presented a semantic description of the spatio-temporal process evolving and mutating features, i.e.
(1) the evolution of a single entity represents basic changes, transformation and movements of a entity, such as (dis)appearance, contraction, displacement, etc.;
(2) a functional process represents change relating to several entities, such as succession, permutation, production, transmission, etc.;
(3) a restructuring process representing spatial topologic change involving several entities, e.g., split, union.

In our case study of Ameland, the landscape processes of foreshore, beach and foredune result in erosion and accumulation of sediments, and they can be described as Features and Spatial objects (Sobj):

- Transmission [Feature(*i*), Feature(*j*), Sobj(*i*), Sobj(*j*)];
- Appear [Feature(*i*), Sobj(*i*)];
- Disappear [Feature(*i*)];
- Union [Feature(*i*), Feature(*j*), Feature(*k*), Sobj(*i*), Sobj(*j*), Sobj(*k*)];

where Feature(*i*), represents the landscape unit *i*, and Sobj(*i*) its spatial extent; Appear(Feature(*i*), Sobj(i)) means that the landscape unit (*i*) appears with the spatial extent of a spatial object (*i*). As the processes are related to the spatial, thematic aspects of landscape unit(s) and object(s), represented by the values based on the grids related to its spatial extent, the data can be structured according to these processes as a process-based view (Fig. 6).

The structure of the spatio-temporal GIS shell

The proposed process-oriented spatio-temporal data model is being implemented in an object-oriented prototype system, which supports environmental modelling by providing a means to predict future events about the real world it represents. The system will provide functions to analyse, model and predict the natural phenomena, through four function modules: ÔData ExplorerÕ, ÔFeature DefinitionÕ, ÔChange IdentificationÕ and ÔDynamic ModellingÕ (Fig.7). Then it accomplishes the modelling process, which includes steps to develop, test and evaluate, and to apply the model (Steyaert 1993).

The ÔData ExplorerÕ module can browse the data and choose the most suitable data for their analysis. ÔFeature DefinitionÕ chooses an appropriate strategy to define the features of interest and to understand the reality. The features can thus be extracted from the temporal data by applying the feature definitions. In the next stage, the extracted features at different moments will be com-

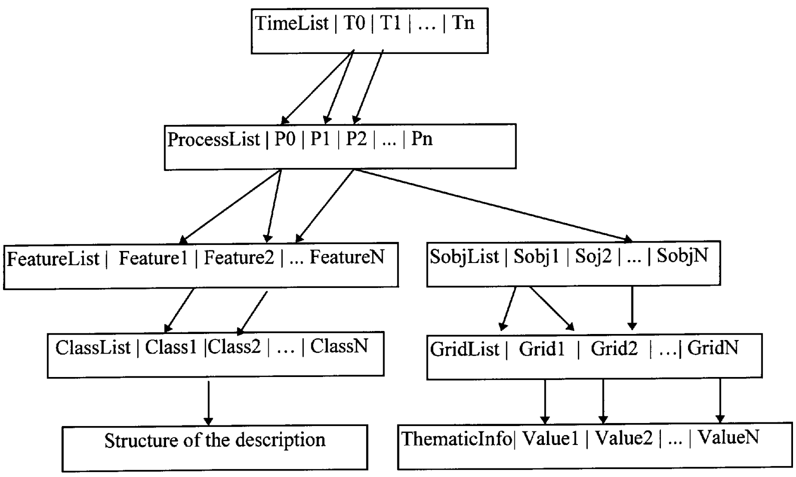

Fig. 6. Process-based view and structure.

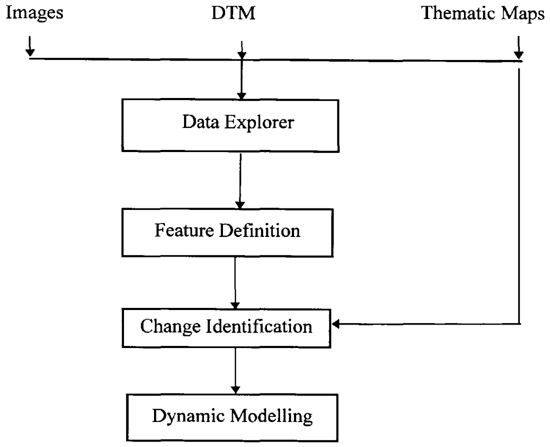

Fig. 7. Logic data flow in a spatial-temporal GIS shell.

pared to identify changes and to build links among them. This process is called ÔChange IdentificationÕ and is implemented in the third module. When the historical links among features are built, the changes of features can be mapped and modelled, a task accomplished in the ÔDynamic ModellingÕ module. Once the models are created, prediction can be made based on existing data.

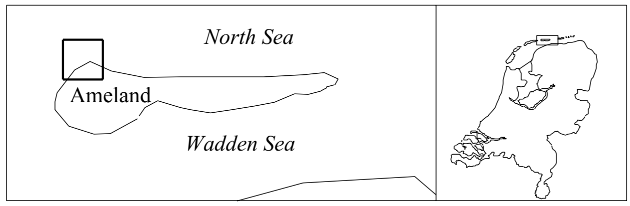

Fig. 8. Location of the study area.

Some results

The afore-explained methodologies are being tested in a case study carried out in the northwest of Ameland (Fig. 8). The elevations of the terrain surface from 1990 to 1995 were processed to model the changes of the (geo)morphology of the coastal zone. Foreshore, beach and dune areas are defined according to their height value. Areas below Ð 1.1 m are considered foreshore, areas between Ð1.1m to 2 m are defined as beach, and areas above 2m are considered foredune. Fig. 9 is a time series of these landscape units extracted from the temporal data. It shows clearly that the (geo)morphology is changing in time, representing erosion and accumulation.

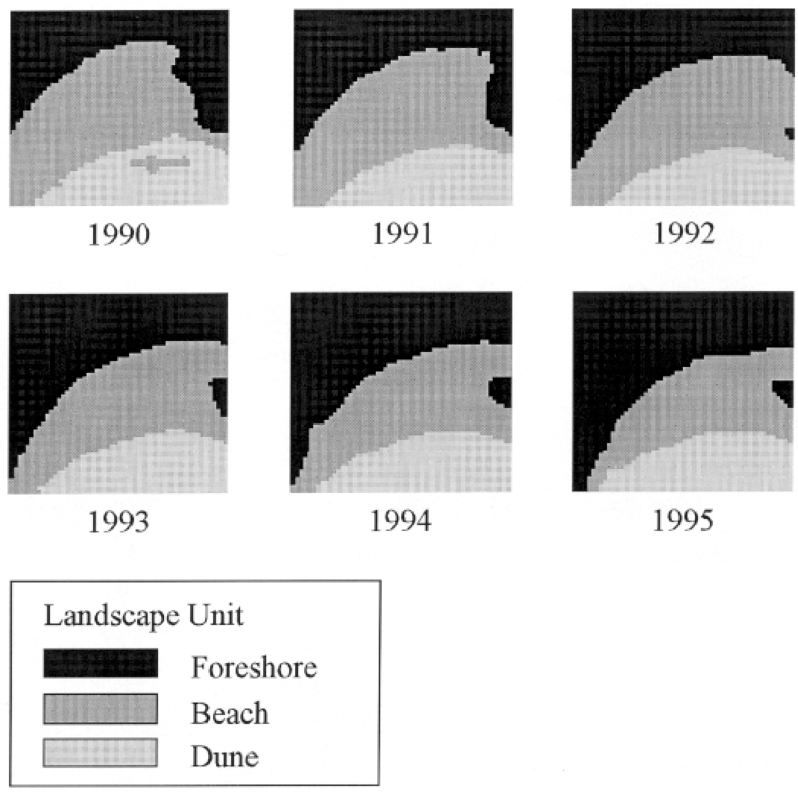

Fig. 9. Changes in the main landscape units of Northwest Ameland (1990-1995).

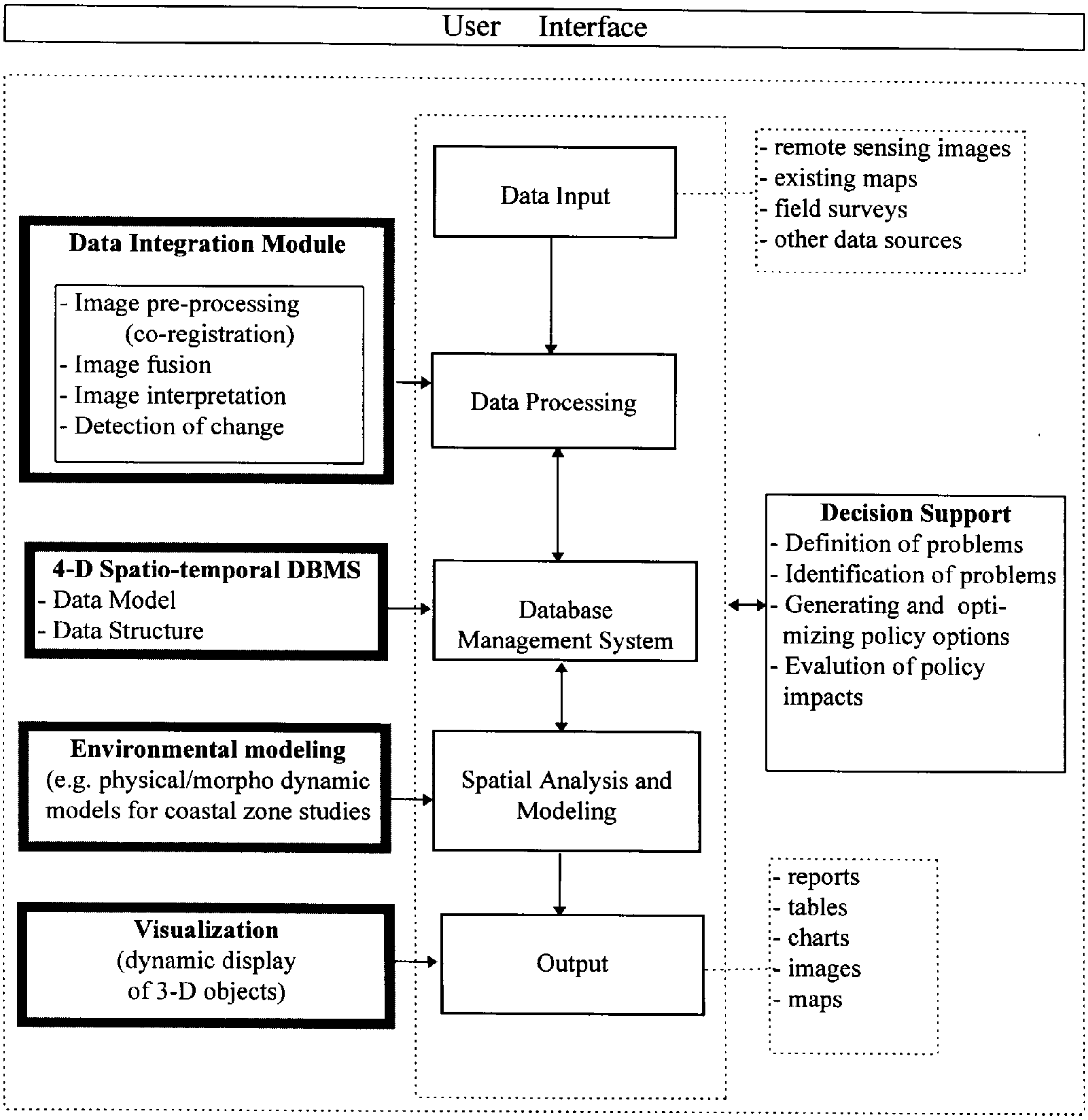

Fig. 10. Structure of the spatio-temporal GIS shell for integrated coastal zone management.

Concluding remarks

The spatio-temporal GIS shell may lead to a method for dynamic modelling, mapping and visualization of phenomena in coastal zones, based on multi-sensor and multi-temporal remote sensing data, GIS techniques and achievements of database management. A practical approach has been suggested based on an existing GIS, complemented by spatio-temporal data models, as indicated in the structural diagram (Fig. 10).

The integration of RS, GIS and Decision Support System (DSS)* technologies in the proposed structure promotes consistent decision-making and supports the evaluation of coastal development alternatives for the coastal zone.

Two perspectives in developing good decision support capabilities of a Geographical Information System can be mentioned:
(1) analytical problem solving capabilities of a DSS which offer modelling, optimization, and simulation functions required to generate, evaluate, recommend, and test the sensitivity or the problem solution strategies, and

*A Decision Support System (DSS) may be defined as an integrated, interactive and flexible computer system that supports all phases of decision-making with a user-friendly interface, data sets and expert knowledge (Bishr 1997).

(2) integration of GIS and specialized analytical models to improve decision support capabilities, focusing on the expansion of GIS descriptive, perspective and predictive capabilities by integrating GIS software with other general software packages (e.g., statistical software) and with specialized analytical models such as environmental and socioeconomic models.

Then, *i.a*., the following can be achieved:

¥ provide a knowledge base and a well structured information system for ICZM (physical, socioeconomic and legislative data);

¥ summarize relevant processes and information for ICZM on which planners and decision-makers may base their decisions;

¥ consider elements of uncertainty and error propagation at different levels of the ICZM process;

¥ trace why a certain alternative is better than others, considering limiting factors and the effects of spatial and temporal distribution in both long-term and short-term processes, impacts and alternatives.

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