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Dynamic GIS Models for Regional Sustainable Development

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1. Introduction

There is an increasing need for improving and extending existing Geographical Information Systems (GIS), leading to integrated policy-oriented systems which may assist planners in complex evaluation problems (Fischer and Nijkamp, 1992). Such systems should provide analysts with several relevant and feasible development scenarios (options). In this context there is also an urgent need for operational models aimimg at reaching ecologically sustainable economic development (SD). On the basis of a compound evaluation, optimum scenarios which meet specific sustainability criteria (Van den Bergh and Nijkamp, 1990; Van den Bergh, 1991; Opschoor and Reijnders, 1991) may then be selected by the user. Moreover, there are several barriers for developing such a system (Nijkamp and Scholten, 1991). The main difficulty arises from the fact that we have to link traditionally complex and data-driven procedures (i.e., GIS procedures; see for example Burrough, 1983; Scholten and Stillwell, 1990; Openshaw, 1990) with procedures that monitor economic-ecological interactions (WCED, 1987; Opschoor, 1991a,b,c). Once we have established the above linkage, we may arrive at a user-friendly and operational system for evaluating SD within the region to which the system is applied. Simplicity and clarity of the system is a necessary characteristic if any strategic or policy decision has to be supported by this system.
In this study we present some preliminary results for such a hybrid GIS-SD system which was developed in the GIS Laboratory of Free University, Amsterdam. The system was also numerically tested in a 90 km (North-South direction) by 100 km (East-West direction) area of the Greek Sporades Islands in the Aegean Sea (Giaoutzi and Nijkamp, 1989). To further evaluate the scenario results, we linked the GIS-SD system to a Decision Support System (DSS), that was originally designed to operate on non-spatial data (Janssen, 1991; Van Herwijnen and Janssen, 1989). In this introductory section we will first start with some background remarks on spatial modelling.

One of the most efficient, computer compatible and elegant scientific approaches of understanding and deepening the processes of real-world phenomena is **modelling**. Models can be defined as idealized, presupposed processes and perceptions that are used to **approximate** the phenomena in the real world. In de Vries (1989) models are accurately and intuitively defined to be "mental maps" of reality. The idealization or completeness of the phenomenon we study is achieved through logical deduction, where the attention is oriented from the whole to its parts, seeking to find simplified and verifiable rules for the function of each part and its dialectic relationships, interdependencies and influences (Rokos, 1989) it has with respect to the other parts. Then, by induction, the whole is again regenerated by its (now explored) parts to its original compound parts (observed by analysis instruments and senses) and is next again compared to reality. The more the deviations this regenerated system (i.e., model) has from reality, the more new deduction-induction processes (i.e., new theory) are required, together with observations, to form an acceptable system (model). "Acceptable" system means here that the deviations of this system from reality cannot be precisely observed or measured. Figure 1 (Mueller, 1987) gives an illustrative view of what a model is in connection with the real world:

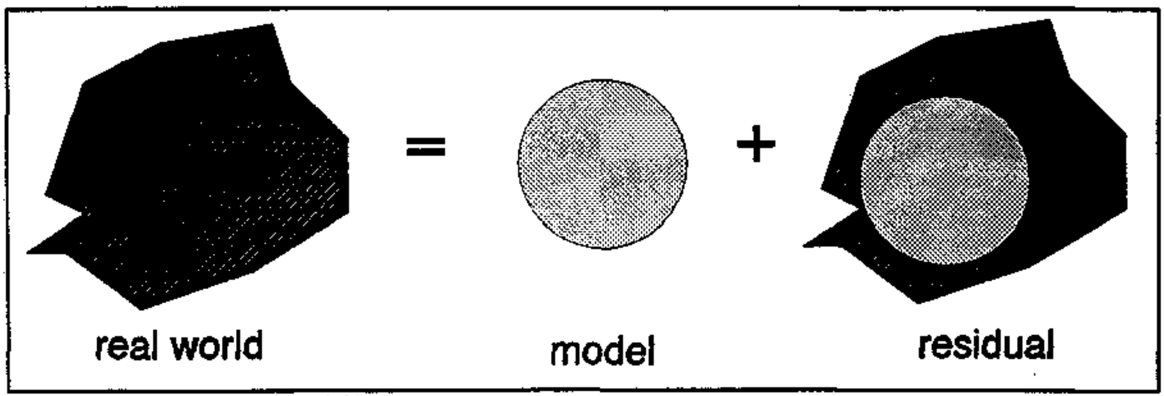

Figure 1: The concept of modelling.

In Figure 1 the concept of approaching the "real world" which has a non-regular geometric shape (meaning a shape that we cannot easily understand and model) with a model (a circle, which is an object of regular shape) is presented. The "remaining" of the real world that has not been modelled is shown as the "subtraction" between the real world's irregular shape and the circle. This residual area is always unknown and if its largest distance from the model cannot be measured or observed by the most advanced technological tools, then our model is ideal for the current spatial and time dimensions referred to. However, the evolution of technology, but also the expansion of human knowledge about social and economic phenomena, arms the researchers with measuring instruments of every kind which can detect reality's deviations from old existing models that have not been taken into account. Then the old models may be improved so that they contain the (systematic) residuals from reality that have been measured. This process continues permanently at both the micro and macro scale of the phenomena, improving our understanding of them.
We will subdivide here the phenomena under investigation into two different broad categories, both dynamic over time, for which a link is searched, viz:

-**geographical phenomena** and
-**economic, ecological and social phenomena**

The basic tool that we will use to analyse the geographical phenomena is GIS dynamic spatial modelling, while the corresponding planning tool for analysing the economic, ecological and social phenomena is the notion of ecologically sustainable economic development (shortly: SD) of a system. Since the publication of the Brundtland report (1987) by the World Commission on Environment and Development, the notion of sustainability has become a major orientation for planning at local or regional levels. These two approaches will be finally linked together for a more general methodology with the aim to link sustainability to GIS.

Spatial non-dynamic dispersion and spatial diffusion models have been already constructed by various researchers in the past. Some examples are the Hägerstrand diffusion model (Morrill et al., 1988), gravity models (Haynes and Fotheringham, 1988), and transportation models (Werner, 1988; Hagishima et al., 1987) etc. In all these models the development process is regarded "frozen" on time, and the object propagation in space due to this motion is deterministically calculated development process is regarded "frozen" on time, and the object propagation in space due to this motion is deterministically calculated by the models at any specific time point. Spatial flow models that used only the distance as a spatial parameter indicated strong spatial correlation of the model residuals (Baxter, 1987), and thus model misspecification may occur when not all spatial registrations (e.g. a 3-D local or national reference coordinate system) are properly taken into account. On the other hand, several studies that aimed at using GIS for monitoring (mainly urban) development have been also carried out in the past (Méaille and Wald, 1990; Lo and Shipman, 1990). These approaches, although giving very useful results for monitoring urban motion, do not incorporate scenario generation techniques, so that the regional sustainability criteria can be applied, not only in an "external event" scenario mode but also in a "policy" and "behavioural" scenario mode. Finally, pioneering studies in applying GIS for "conservation databases generation" (a concept which is close to sustainability considerations) have also been conducted in the past (see e.g., Ahearn et al., 1990), but again the spatial dynamics was not considered.

It is thus evident from the above discussion that there is a missing node between the field of GIS modelling and non-spatial modelling which would be necessary to integrate most of the benefits from both fields in a dynamic sense. In this paper, we aim at providing this missing link, in a both theoretical and operational framework.

In Section 2 non-spatial modelling concepts are discussed, while in Section 3 the discussion is focussed on spatial modelling theory, where both are examined in a dynamic framework.

By creating in this way the desired background for the necessary methodologies and tools that are needed, the concept of **generalized stocks-layers** is introduced in Section 4. This concept aims at providing the theoretical modelling link between GIS and SD modelling as already discussed above. Error analysis considerations are provided in section 5, which aim to determine the error sources that contribute to the total error budget of the above hybrid models. Finally, preliminary numerical results concerning the application of the GIS-SD system to the Sporades Islands in the Aegean Sea, Greece, will be outlined in Section 6.

In the next section the general concepts of modelling (non-spatial) economic-ecological-social phenomena are given first, so that the main characteristics of existing models of this type are briefly explained.

2. Non-spatial Models

The concepts and definitions of SD can be summarized in the following statement of the World Commission on Environment and Development (WCED, 1987) in the so-called Brundtland report: "Sustainable development is a pattern of development that meets the needs of present generations without jeopardizing the ability of future generations to meet their own needs". See also Nijkamp and Soeteman (1990), Van Pelt et al. (1990), Opschoor and Reijnders (1991), Van den Bergh (1991), and Archibugi and Nijkamp (1989).

Traditionally, these economic and ecological SD studies, being complicated in themselves, are dynamically modelled using mainly **time** as an independent variable. For example, the general form of a dynamic economic or ecological model can be written as a set of ordinary simultaneous differential equations as follows (see also de Vries,

$$\frac{dX_i(t)}{dt} - F_i(X_1(t),\ X_2(t),\ \ldots, X_n(t);\ \Phi : t) \qquad (1)$$

where $X_1(t), X_2(t), \ldots, X_n(t)$ are components of the n-th dimensional vector space V^n (state vectors) which are fully describing the behaviour of the system under investigation;
Φ is the vector of the parameters that characterise the system's structure and context; and
t is the independent (continuous) variable.

The initial state vector of the system is assumed to be known: $X_1(t_0), X_2(t_0), \ldots, X_n(t_0)$ are given at the initial time t_0 and the system 1 is computed for $t \geq t_0$. The main reasons that make a system of differential equations suitable for dynamic modelling are the following:

1. In nature, we usually know the theoretical velocities (flows) or accelerations (rates of flows) of some quantities more accurately than the quantities themselves. This stems from the fact that we have already models available which can describe the motion of an object, a stock etc. very accurately if the **forces** that produced this motion are (assumed to be) known. A traditional example from a mechanical analog is the equation of motion of a body under the influence of a (constant in time) force F:

$$m \frac{d^2r}{dt^2} - F \qquad (2)$$

where **r** is the position vector from the origin of the coordinate system to the body of mass m which accepts a force of magnitude F. Any complications in (2) can easily be formulated in terms of additional forces (which will be included in the right hand side of the equation) and additional displacements (which will be included in the left hand side of the equation), always according to Newton's fundamental law.
The simulation of dynamic phenomena in social sciences can also be successfully approached by introducing (2) as a basic "motion" or "development" model. In such type of social models any spatio-temporal movements of objects (urbanization, tourism, migration etc.) are inserted into the left hand side of (2) and are to be interpreted as movements that were caused by external forces of any type (attractiveness, job opportunities, building efficiency etc.) that reside in the right hand side of (2). In our work we will use this concept to link geographical (on the one hand) with socio-economic and ecological (on the other hand) models.

2. There is usually little or no knowledge at all about the analytical solutions for systems of the form (1). This is mainly due to the fact that system (1) contains in the right hand side all (or part of the other) state vectors that describe the system; thus an analytical solution may be very difficult, or sometimes impossible. The physical meaning of this is that the change in time (or motion) of each state vector is influenced by all the other system's state vectors and parameters, thus making the model(s) complicated and impossible to have an analytical (and thus deterministic) solution.

3. The **initial** conditions of a system at a specified time t_0 can be measured or determined with theoretically infinite accuracy. This is due to the fact that, without loss of generality, we can regard the system under investigation "frozen" in time t_0 and either physically measure its state vector at that time, or determine it through easier (deterministic) models. The mechanical analog from mechanics (equation 2) is that the initial positional vector of the body $\mathbf{r}=\mathbf{r}(x_0,y_0,z_0)$ can be specified very accurately either by physically measuring these coordinates, or by specifying them through easier models (e.g., from a "force-free" motion of the body which results in constant velocities).

4. Models of the form (1) can be numerically integrated using standard numerical integration techniques (Press et al., 1986), which are suitable for implementing in today's computers, having a high performance in speed, accuracy of the results and formulation efficiency, no matter how complex systems (1) can be. In general we can also eliminate the round-off errors of the numerical solutions well beyond the desired observational accuracies of our model. More details on numerical integration will be given later in this section.

5. There is full **control** for the results of each time step dt that is used to integrate (1). Thus any **constraints** regarding the "external events" that result from the solution of (1) alone can be added at any stage of the numerical solution, allowing thus for efficient **scenario generation**.

It should be noted that complex second- or higher-order differential systems can always be reduced to first-order systems by proper substitutions and thus turn out to be of the form (1). In a reverse way, formulation (1) does not necessarily mean that our system is a system of first-order differential equations, since the structure of this system's formulation can equivalently result in a system of second- or higher-order differential equations.

Continuing the analog concept of mechanics when studying economic-ecological models we can view the original state vectors X_i as a system of **stocks** S_i which dominate the operation of the system. In this case the derivatives dS_i/dt are the **flows** of the stocks through time, and the right hand side of (1) can be a function of stocks, flows, constants, and, of course, time (see also Hordijk and Nijkamp, 1977). Other functions of stocks, flows or constants that can enter the right hand side of (1) are called **converters**. A specific modelling tool, STELLA, has been developed in (Richmond et al., 1987), from where the majority of the above terminology has been adopted, and which we will briefly discuss here.

The generation of a model in which the modeller assigns the stocks, flows, converters and constants is done in a interactive graphical way, where a menu of these main modelling "objects" is available (Figure 2). The above modelling steps result in the following system of differential equations (equations 3):

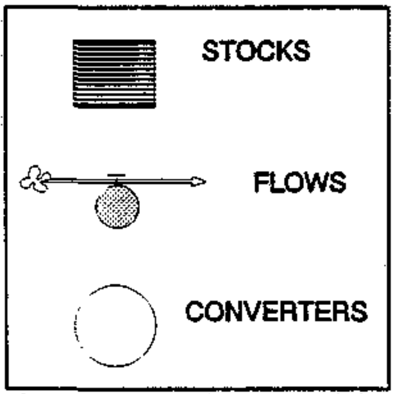

Figure 2: The basic menu entities used for modeling in STELLA software.

$$\frac{dS_i}{dt} = F_i\,(\,S_1,\ S_2,\dots,\ S_n;\ C_1,\ C_2,\dots,\ C_k;\ t) \qquad (3)$$

with the initial conditions (equations 4)

$$\begin{aligned} &S_1(t_0)=INIT(S_1)=S_{10}\\ &S_2(t_0)=INIT(S_1)=S_{20}\\ &\quad\vdots\\ &S_n(t_0)=INIT(S_n)=S_{n0} \end{aligned} \qquad (4)$$

An example from mechanics can again be given. Consider the spring-mass system (Figure 3):

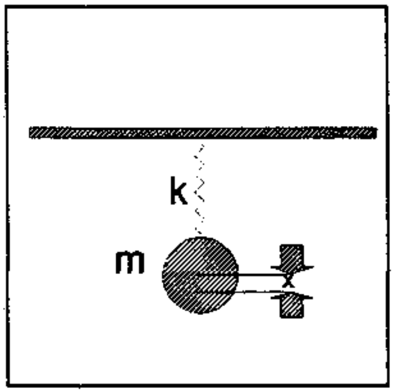

Figure 3: The mechanical example of spring-mass system.

The differential equation of motion for this system is a second order differential equation:

$$\mathbf{m\ d^2x/dt^2 = -kx} \qquad (5)$$

where m is the mass of the spring,
k is Hook's spring constant, and
x is the displacement.

The above system can be reduced to a system of two first order differential equations, as follows:

$$\begin{aligned} &dx/dt=v\\ &dv/dt=-(k/m)*x \end{aligned} \tag{6}$$

Thus the system under investigation is fully represented with two stocks, namely the stock of velocities v and the stock of displacements x. The flow of x, dx_dt, is the velocity and the flow of v, dv_dt, is the acceleration expressed as in (6). The converters are in our case the constants k and m. The corresponding diagram using the notations of Figure 1 is shown in Figure 4:

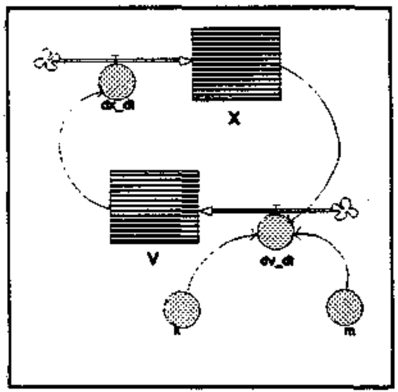

Figure 4: The spring mass model as a STELLA diagram.

Assuming that the initial numerical values for the stocks and the constants given by the user are e.g. m=1, k=1, INIT(x)=1, INIT(v)=0, then as soon as the user finishes up "sketching" the model, the following system of first order differential equations has been created (equations 7):

$$\begin{aligned} &x = x + dt * (dx\_dt)\\ &\mathrm{INIT}(x)=1\\ \\ &v = v + dt * (dv\_dt)\\ &\mathrm{INIT}(v)=0\\ \\ &dx\_dt=v\\ &dv\_dt=-(k/m)*x\\ \\ &k=1\\ &m=1 \end{aligned} \tag{7}$$

When we run the model for e.g. $t_0=0$ till t=24 (hours) with a time step (dt) of 0.125 (hours), then the sinus and cosinus graphs for stocks x and v appear correspondingly. This is evident from the analytical solutions of (7), which are of the form x=asin(wt),y=acos(wt).

The modelling and simulation language on which the above tool is based is DYNAMO, which is one continuous simulation language. Other simulation languages are: **Continuous:** Continuous System Modelling Program **(CSMP);**

Discrete: GPSS, SIMSCRIPT, GASP and SIMULA (see Wyman, 1970).

From the above the need to properly utilize this valuable tool which has been designed for **non-spatial** dynamic modelling for modelling **spatial** phenomena is evident, **within** a geographical information system. The proper integration involves several steps which will make possible the efficient data input-output, modelling and scenario generation. A first, very important step, that has to be taken is the creation of an interface between the existing modelling tool (written in **Apple Operating System**) and the majority of the existing geographic modelling packages (written in **IBM** or **Microsoft Diskette Operating System**). For the creation of this interface we selected an efficient, tested and "certified" language among the scientist's computer languages, the **FORTRAN** language (Microsoft, 1989). The logic in forming the above interface followed similar lines as in the procedure of forming the corresponding models in a STELLA environment.

3. Spatial Modelling

Now we will discuss the field of spatial models (see Scholten and Stillwell, 1990), by expanding the discussion presented in the previous section in spatial models.

In writing the systems of equations (1) we assumed that there is only **one** independent variable, namely time t. We could then investigate the interaction of various different quantities by relating them to stocks and assigning the proper relations for their flows, intermediate converters and constants.

On the other hand if we forget for the present time this dynamic concept of modelling and assume that we examine an object (e.g. a region) "frozen" in space and time by using geographical spatial modelling, the following concepts can be defined:

A specified region on the surface of the earth (or either above or below it, in a generalized context) presents, in general, a variety of phenomena that need to be analyzed (Figure 5). The complexity of the region under investigation is exponentially increasing with:

a) the scale of the region, starting from the large scales of 1:500 till the small scales of 1:1000000,

b) the types of land uses of the region, starting from areas with a single land use (e.g., agriculture only), and proceeding to areas with multiple land uses and urban areas,

c) the geographic location of the area (geographic latitude, longitude and elevation), and

d) the frequency of the terrain changes within the specified region, starting with smooth areas and proceeding to rough and mountainous areas.

In Figure 5 we can see a "sample" region on the earth's surface presenting a landscape with some houses, rivers, roads etc. The region is analysed in terms of **layers** (Burrough, 1983) of information, each layer assuming to be as independent as possible from the others (avoiding redundancy of information) and as complete as possible in the attributes it is representing (avoiding loss of information). The origin of the spatial three-dimensional (x,y,z) reference system is located "somewhere" on the earth and is usually defined by surveying and geodetic methods. All layers are assumed to refer to the same coordinate system, i.e. they are geometrically corrected. We thus form a **spatial** model of the real world which is analytical and tries to decompose the

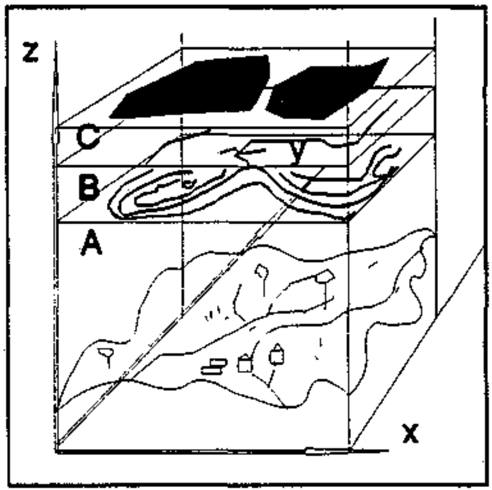

Figure 5: The concept of overlaying a region with layers A,B,C etc.

real world into somewhat simpler components, which can be mathematically described and measured. We can then write the general equation for a spatial static process R(x,y,z) (in analogy with equation 1):

$$
\begin{aligned}
&R(x,y,z) - F(A,\ B,\ C,....,Q) \quad with \\
&A-A(x,y,z) \\
&B-B(x,y,z) \\
&. \\
&. \\
&Q-Q(x,y,z)
\end{aligned}
\qquad (8)
$$

The layers A,B,C,.. can be one of the following attributes, or aspects, of reality:
- Topography (Digital Elevation Model, DEM)
- Land Uses
- Hydrology
- Transportation
- Thematic information
- Demographic data
- Population distribution
- Watersheds
- Slopes, Aspects gradients of the terrain
- Cadastral information
- Public utilities (sewing, water etc. networks)
- Remotely sensed satellite images
- Digitized air-photographs
- Meteorological data (rain heights, temperatures etc.)
- Pollution data
- Ecological species distributions
- Historical data (documents), etc.

It is therefore obvious that in A,B,C,..Q point, line areal and volumetric types of information can appear. Each one of these layers can then be regarded as a map of the same region and properly geometrically registered with the other maps. To digitize all above layers so that they can be included in a fully computerized geographical information system, the following should be considered:

Depending on the **resolution** that each of these layers requires (or superimposes depending on the data collection method that was a priori followed), the **representation** of these layers may be done in any of the "traditional" computer data structures, namely in a **raster** or in a **vector** format. Thematic-type of depicted information, land-uses, raw and classified satellite data, digitized air photos etc., are usually stored in a raster format; cadastral information, roads and public transports, watersheds etc., that normally require high internal representation accuracy are stored in vector format; elevation models, slopes, gradients, aspects etc. can be stored in either raster or vector format.

Let us assume that we have stored layers A,B,C,.., etc. in a geographic system, forming a database. Each layer represents a specific type of spatially referenced information of the form:

$$K=K(x,y),\quad K=A,B,C,..Q \tag{9}$$

To be in a position to properly access the database we created we need first to **classify** the stored information into meaningful and efficient numeric intervals. For example, if $Z=Z(x,y)$ in (9) represents a digital elevation model, then most probably the range of the elevation function Z will be between zero and some positive number, say 1000m. All the intermediate numbers in [0,1000] can appear in this data base. To be able to access this information in a more "user-friendly" way, we have to assign **classes** of information, e.g.:

Class 1 : [0m,300m) ; low elevations
Class 2 : [300m,700m) ; medium elevations
Class 3 : [700m,1000m] ; high elevations.

In this respect the original file is "transformed" through the use of look-up tables to a file in which alphanumeric descriptions for each classification scheme become possible. This zoom-out of the layers is very important for the analyst since he can reduce the resolution level of the original data base for analysis purposes.

After we decide on the classification schemes, we obtain the classified layers (equations 10)

$$\begin{array}{l} A{:}\ A_1(x,y),\ A_2(x,y),\dots,A_l(x,y) \\ B{:}\ B_1(x,y),\ B_2(x,y),\dots,B_m(x,y) \\ . \\ . \\ Q{:}\ Q_1(x,y),\ Q_2(x,y),\dots,Q_p(x,y) \end{array} \tag{10}$$

Since l,m,..,p are not large numbers (usually in the order of 10 for land uses, 16 for elevations, 5-6 for slopes and aspects etc.) we can assume that, in this thematic-type of data representation, there is a generalization of information and thus the classified data bases can then be stored in raster format. This of course does not mean that any higher accuracy of the original databases should not be present any time we need it.

In doing so we arrive now at the next step of spatial modelling, which is a design of a tool that will enable us to simultaneously **access** a part or the whole of the created databases of layers, i.e. will allow us to:

- **Edit** the created layers either in a graphical or in a text (manual) form;
- **Update** the layers with new input data information that may become available, by digitizing or rasterizing other sources of information;
- Perform any **algebraic operations** among them and create synthetic (new) layers;
- Perform **statistics** (e.g. multivariate analysis) and **correlations** (e.g. cross-correlation coefficients) between the different layers;
- Perform **simultaneous queries** of logical and numerical form;
- Display **Graphically** the results to maps, reports or tables for further processing and decision making.

In other words we now seek for a geographic system which will have inherent capabilities of a **relational data base management system**, together with extra statistical analysis capacities and graphical representation of the results.
A number of GIS spatial analysis tools exist that partially or completely attempt to fulfil the above requirements. The choice always depends on the specific application. The tool that was used in this study for multiple-layers creating and accessing is **SPANS** (SPANS, 1990). In this tool the user can enter geographic data from digitizers, manually, or by transforming existing types of data. The various layers of information can be created from point, line, or areal data in vector or raster form with as user-specified classification scheme. There is a further internal compacting of the original data to **quadtrees**, a data compression method. All the created layers can be stored in a quadtree format in a user-specified resolution which depends on the a priori established scale of the region and the data accuracy, transformed in spatial dimensions. The highest resolution that can be recovered from a quadtree map is the highest raster resolution of the original data. The simultaneous processing of the layers (up to fifteen at the same time) can be done while the layers have been transformed in quadtrees and thus we can erase the original (raster or vector) files. There is also in internal programming language which allows for spatial modelling in a batch mode. The results (tables, reports, maps) can be saved on disk in the form of "slides" for fast displaying and presentations.
For a modified run-length encoding compression form that gives comparable results with the quadtree form, see Despotakis (1990).

4. GIS Spatial Models for Sustainable Development

We have now reached a crucial point where a **link** between the non-spatial models of type (3) and spatial models of type (10) has to be found. From the discussion of the present and the previous section it can be easily seen that the two ends of the linking thread between SD and GIS have been simultaneously developed: The non-spatial concepts of the models of type (3) are first given to enter the ideas of stocks and flows and their dynamic interrelations over time, but "frozen" in space. Then, a summary of the layering processing, and their dynamic interrelations in space, in geographic modelling is given, considered "frozen" in time. The representative tools from both sides were the STELLA non-spatial modelling from the one side and the SPANS spatial modelling on the other side. Thus in the modelling process in the framework of sustainable development constraints, the next natural question that follows is: "how can we model dynamic phenomena in time, considering also their spatial dimensions, within the framework of sustainable development?" It is evident that an answer to such question will have to **integrate** both given modelling approaches in one, together with the sustainability constraint.

We begin to investigate this problem by regarding the conceptual equivalence of **stocks** with **layers** (in Murthy et al. (1990) they are also referred to as '**reservoirs**' or '**levels**' interconnected by flow paths): We could write e.g. for layer A(x,y) in (10) and stock S_i in (3) the following relationships:

$$\begin{array}{c} A_1(x,y) \leftrightarrow S_1(t) \\ A_2(x,y) \leftrightarrow S_2(t) \\ \vdots \\ A_l(x,y) \leftrightarrow S_l(t), \end{array} \tag{11}$$

i.e. relate the idea of stocks with the idea of layers by realizing that the spatial contents of a specific classified layer (classes of layer A in the example of (11)) can be regarded to be stocks which dynamically change in time. In this manner we can generalize the concept of dynamic modelling of a specific phenomenon to include all the necessary stocks S_i which are needed to decribe the available spatial layers of information for a region. From the above it is evident that if there are t spatial layers available for a region, each with l,m,..,q classes (see equation (3)), then we need r=l+m+..+q stocks (and flows) definitions of the form (10). Thus our generalized spatial modelling of dynamic phenomena takes the form:

$$dS_i/dt=F_i(t,x,y,z;\ S_i\ ;\ F_i\ ;\ C_i),\ i=1,2,..,r \tag{12}$$

with the initial conditions

$$S_i(t_0,x_0,y_0,z_0)=INIT(S_i)\ ,\ i=1,2,..,r \tag{13}$$

Then the sustainable development considerations can be embedded in (12) and in each integration step dt by:

1) imposing the necessary **conditions** that stocks S_i should fulfil
2) defining and examining the values of the **indicators** (but also the stocks, flows and converters themselves) as functions of the stocks, flows and converters, and
3) defining and examining alternative **scenarios** which, by the proposing system, can be of any kind: No-policy (external events) scenarios (natural progress of the eco-system), external policies (influence totally or partially one or more functions of the eco-system) and behavioural scenarios (creating and monitoring spatial dynamic behavioural patterns such as migration, urban growth etc.)

The important stage for the above link is to decide on the rules of three types of **stock motion**: 1. Expansion, 2. Shrinkage and 3. Migration.

These rules have to govern the propagation of the stock changes that will result from the dynamics on time solution to the spatial geographic system. Such rules can be built in a raster (or quadtree format) and will reflect the spatial reality of the region. For example, if the dynamic solution gives an increase in "urban stock" of the land-use layer of $10000m^2$, then the spatial model can equally (this can be an assumption, and unequal changes in x and y can be as well treated) increase the x and y dimension of this class by the square root of 10000=100m. The "candidate" squares in the geographic layer that can accommodate this expansion will be determined by overlaying the land-use layer with other layers that can influence this expansion: the layer of slopes, aspects elevation, transportation etc. (see also Méaille and Wald, 1990). Of course the interaction of each class within the same layer will also play an important role.

After all the "motion" assignments will have been completed to the geographic system, in a hybrid user-computer manner, then the results (maps,reports etc.) for this time stage will be written on disk, and the numerical integration will proceed to the next step.

The proposed system is shown in Figure 6: Sustainable development constraints can be entered at the "expansion rules formation" stage, after each integration circle has been completed. These constraints can be of the form (14) (equality constraints) or of the form (15) (inequality constraints):

$$G_{SD}(S_1, S_2, \ldots, S_r) = 0 \qquad (14)$$

$$G_{SD}(S_1, S_2, \ldots, S_r) \geq 0$$
$$G_{SD}(S_1, S_2, \ldots, S_r) \leq 0 \qquad (15)$$

The user can enter the modelling procedure for **scenario generation** at three points: in the differential equation forming and editing process, in the geographical analysis stage and at the "expansion rules formation" after each integration step (Figure 6). The cooperation of the non-spatial (STELLA) with the spatial (SPANS) system is achieved through the generalized stocks that form the function of layers. The transition to the space domain is achieved by defining the rules of stock motion.

It is evident that the outputs of this system can be further analyzed and evaluated by a decision support system linked into it.

The proposed system in essence employs concepts from the combined fields of economics, geographic information systems, animated cartography (see also Koussoulakou, 1990), and surveying.

5. Error Analysis.

We conclude this section by focusing on the errors that are entered into the model from the various error sources (see also Heuvelink et al., 1989). These error sources can be subdivided into three categories:

- **Numerical integration errors**
- **Locational and attribute errors in overlaying procedures**
- **Errors due to mathematical models**

Each error source is next separately discussed, with the ultimate goal to develop the theoretical error studies frame for the proposed hybrid system. Numerical results will be presented in the future, based on the theoretical discussions that follow:

-Numerical Integration Errors

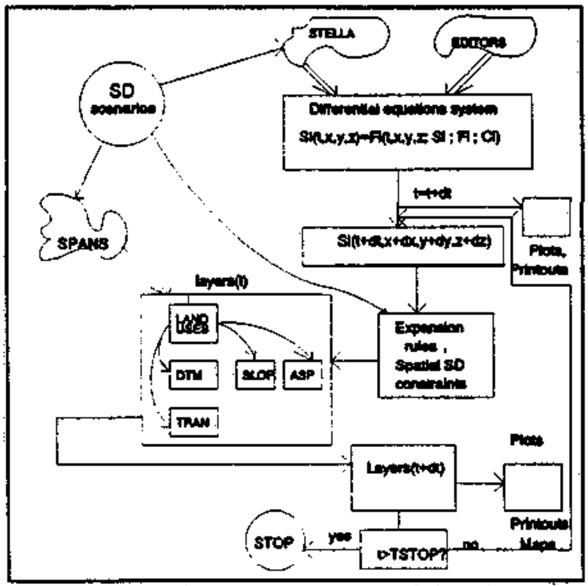

Figure 6: The link between non-spatial and spatial dynamic modelling.

These error sources contribute to the general error of the computed quantities when this technique is used in combination with any other modelling (spatial or non-spatial) analysis.

The numerical integration method selected in this study is the Runge-Kutta 4th order method. In terms of accuracy it stands somewhere "between" the Euler method and the advanced **predictor-corrector** methods. In increasing degree of accuracy these methods are as follows (only one variable is given here for simplicity: integrate $y'=f(t,y)$ with $y(t_0)=y_0$.):

Euler method: $\quad \mathbf{y(t+dt)\approx y(t)+dt*f(t,y)} \quad$ **(16)**

This method is also employed by STELLA for integrating models with limited accuracy demands. Since convergence problems may occur only because of the use of this specific method (i.e. our modelling may otherwise be perfect), it is suggested that this method is rarely used, even if increase in computational time has to be a sacrifice.

Runge-Kutta method: $\mathbf{y(t+dt)\approx y(t)+(1/6)*(k_1+2k_2+2k_3+k_4)}$ **with :**

$$\begin{aligned} &k_1=dt*f(t,y)\\ &k_2=dt*f(t+dt/2,y+k_1/2)\\ &k_3=dt*f(t+dt/2,y+k_2/2)\\ &k_4=dt*f(t+dt,y+k_3) \end{aligned} \qquad (17)$$

The advantage of this method is that it avoids the computations of higher order derivatives, and still approximates the solution using an equivalent of fourth-order Taylor expansion. In place of these derivatives extra values of the given functions f(t,y) are used.

Predictor-Corrector methods: They are based in a formula to make a first prediction of the next y(t+dt) value (predictor) . This prediction is then followed by an application of a more accurate formula (corrector). This procedure, although complex, has the advantage that with each approximation an estimate of the error can be made and thus we have better control of the propagated error in each integration step. We give here the most famous prodictor-corrector methods: The Milne method and the Adams method (Scheid, 1968):

Milne method: Uses the predictor-corrector pair:

$$y(t+dt)\approx y(t-3dt)+(4dt/3)(2y'(t-2dt)-y'(t-dt)+2y'(dt))$$
$$y(t+dt)\approx y(t-dt)+(dt/3)(y'(t+dt)+4y'(t)+y'(t-dt)) \qquad (18)$$

Adam's method: Uses the predictor-corrector pair:

$$y(t+dt)\approx y(t)+(dt/24)(55y'(t)-59y'(t-dt)+37y'(t-2dt)-9y'(t-3dt))$$
$$y(t+dt)\approx y(t)+(dt/24)(9y'(t+dt)+19y'(t)-5y'(t-dt)+y'(t-2dt)) \qquad (19)$$

In both the above methods the computation of the four previous values: y(t), y(t+dt), y(t+2dt) and y(t+3dt) are required before the numerical integration begins.

The **sources of error** for the Runge-Kutta procedure that we utilize, are the following (see also Scheid, 1968):
- First, we note that in writing equation (17) the "approximately equal" sign was used. This means that the series is **truncated** at a specified order of expansion and this error source is called **truncation error e_T**. It depends on the fifth order derivatives of y, $y^{(5)}$ and on the fifth power of the time step used (dt^5). The **local truncation error** (i.e. the error made at a specific integration step) and in some cases the total truncation error can be reduced by using the method of **adaptive stepsize.**
- A second error source is the **propagation error e_P**. It results from the propagation of error in the initial value(s) y_0 throughout the numerical integration procedure, and depends also on the magnitudes of the first, second, third and fourth derivatives of y. It can be (although in an elaborate way) computed by applying the law of propagation of errors in (17). To reduce this error source we have to reduce as much as possible the errors in the initial values.
- Implementing the procedure in a computer, the **round-off error e_R** is always present. It also propagates through each step of integration, and sometimes it can be the dominant error in the whole procedure. The treatment of this error is achieved by increasing the internal numerical accuracy of the computations (and, in turn limiting the available memory). In FORTRAN this is done by transferring the real numbers byte domain from 4 (single precision REAL*4) to 8 (double precision REAL*8).
- In approaching a continuous phenomenon in nature by a set of differential equations and solving this set as above by a **discrete** time stepsize dt, we introduce an error which we may call **discretion** or **discretization error e_D**. Reducing dt as much as possible does reduce this error, but it gives an exponential increase in the round-off error (and, of course, the amount of necessary computations and memory requirements). It is thus suggested that for the treatment of this error the **adaptive stepsize** control is again used.

From the above four different sources of errors we can form the **total numerical integration error e**, assuming that the four separate errors are **uncorrelated** as:

$$e=(e_T^2+e_P^2+e_R^2+e_D^2)^{1/2} \qquad (20)$$

The ratio of the total error to the exact solution (which is sometimes impossible to estimate if the exact solution is not known), called the

relative error e_r, is of high importance since if the exact solution grows larger in absolute value, then also a larger total error can probably be tolerated.
We finally give some remarks about the **stability** and the **convergence** of the solution obtained by using (17). The solution is defined to be **stable** if any single error made in applying the Runge-Kutta (or any numerical integration method) to y'=Ay (see also de Vries, 1989) has an effect which imitates the exact solution behaviour. On the other hand the **convergence** of the solution to the exact solution is important and it mainly depends on the existence and beahaviour of the higher order derivatives.

- Locational and Attribute Errors in Overlaying Procedures

We should notice here that the **error propagation** of the original data into the formed layers should be considered as carefully as possible. The various error sources that enter the overlaying procedures of real-world phenomena (see Figure 5) could be summarized as follows:

- **Round-off error l_R**, which results from the same source as it was previously described,
- **Discretion error l_D**, which results from the discretized approximation of continuous phenomena. This error is much larger in raster and in quadtree than in vector representations. This error can be diminished by choosing as small a spatial stepsize as possible (dx*dy*dy), always stopping at the point where the l_R error resulting by this procedure becomes larger than the discretion error itself.
- **Propagation error l_P**, which results from the propagation of the errors $\sigma_K(x,y)$ in the original data K(x,y), K=A,B,C,,Q when forming synthetic layers U(x,y) as functions of the original layers: U(x,y)=f(A,B,..,Q). This error depends strongly on the first derivatives of functions A,B,C,..Q, their variance-covariance matrices, and their error correlations that may exist between them. If layers A,B,C,..,Q are uncorrelated, then their errors are also regarded to be uncorrelated. In real-world applications, however, this is not the case, since the extraction of the original data that form layers A,B,C,..Q from various techniques (maps, air-photographs, satellite sensors) can sometimes be strongly dependent to each other. We can somehow control this error by a proper data editing to detect and disregard **blunders** (robust estimation), and by comparing a data source with another (independent) data source of the same region.
- **Locational error l_S**, which results from the uncertainty in position the various data layers imply. Even after the proper geometric registrations there remains an uncertainty in position coordinates (x,y,z) which can be expressed by the variance-covariance matrix of the (computed or measured) coordinates (equation 21):

$$\Sigma_{xyz}=\begin{pmatrix} \sigma_x & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_y & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_z \end{pmatrix} \qquad (21)$$

One way to study this error is through Monte-Carlo methods, i.e. changing randomly the positional coordinates x,y,z, perform geographic operations (i.e. compute U=f(A,B,C,..,Q)) and compare the results with an expected value of this geographic operation (i.e. a mean value of U).

- **Attribute error** l_A, which results from the errors in labelling the various classes A_1, A_2,..,A_l in (11). This error can be regarded as a blunder type of error, and can be removed with field control.

- The **total error** l of the overlaying procedure can then be estimated, assuming that all its error components are uncorrelated through:

$$l=(l_R^2+l_D^2+l_P^2+l_S^2+l_A^2)^{1/2} \qquad (21)$$

Concluding this section on spatial modelling, the theoretical concepts of layers, their geometric registrations, and their incorporation into a relational data base management system were given, together with some error analysis considerations, considered to be essential a-priori knowledge for the desired link between SD and GIS modelling.

- Errors due to Mathematical Models

The mathematical spatial and non-spatial GIS-SD models are only approximations to the corresponding real world's models. This means that even if the numerical integration errors and the overlaying errors were zero, there would still exist an error source due to the imperfection of the mathematical models themselves. This error source has usually a systematic pattern, and this is how it can be detected by instruments, provided its magnitude is higher than the instrument's sensitivity. It is only through this type of error research that we can improve our knowledge about the real phenomena. By detecting them, we usually arrive at more precise and refined mathematical expressions of reality. However, for the detection of such errors, high external observations precision and minimization of the error propagation is assumed.

6. Empirical Results

The GIS-SD system developed as described above was numerically applied to the Greek Sporades islands located at the central and western part of Aegean Sea (Figure 7).
There are two main conflicting objectives that appear in the Sporades area and, consequently, are dealt with in this study: (1) regional economic development and (2) environmental protection. The economic activities of the approximately 20000 inhabitants of the region (1990) are mainly based on tourism and fishery. The dramatic increase of tourism in the past 30 years in Greece has also influenced in descending order the islands: Skiathos, Skopelos, Alonnisos and Gioura. Pilion is expected to receive spill-over effects from tourism and agriculture. During the summer there is a strong increase of population on the islands due to tourism (domestic and foreign). This population increase often exceeds the population carrying capacity of the islands, and may thus result in abrupt high resource demands. This in turn may cause irreversible processes in the resource stocks. Similar effects caused by the abrupt changes in economic activities due to the tourism have

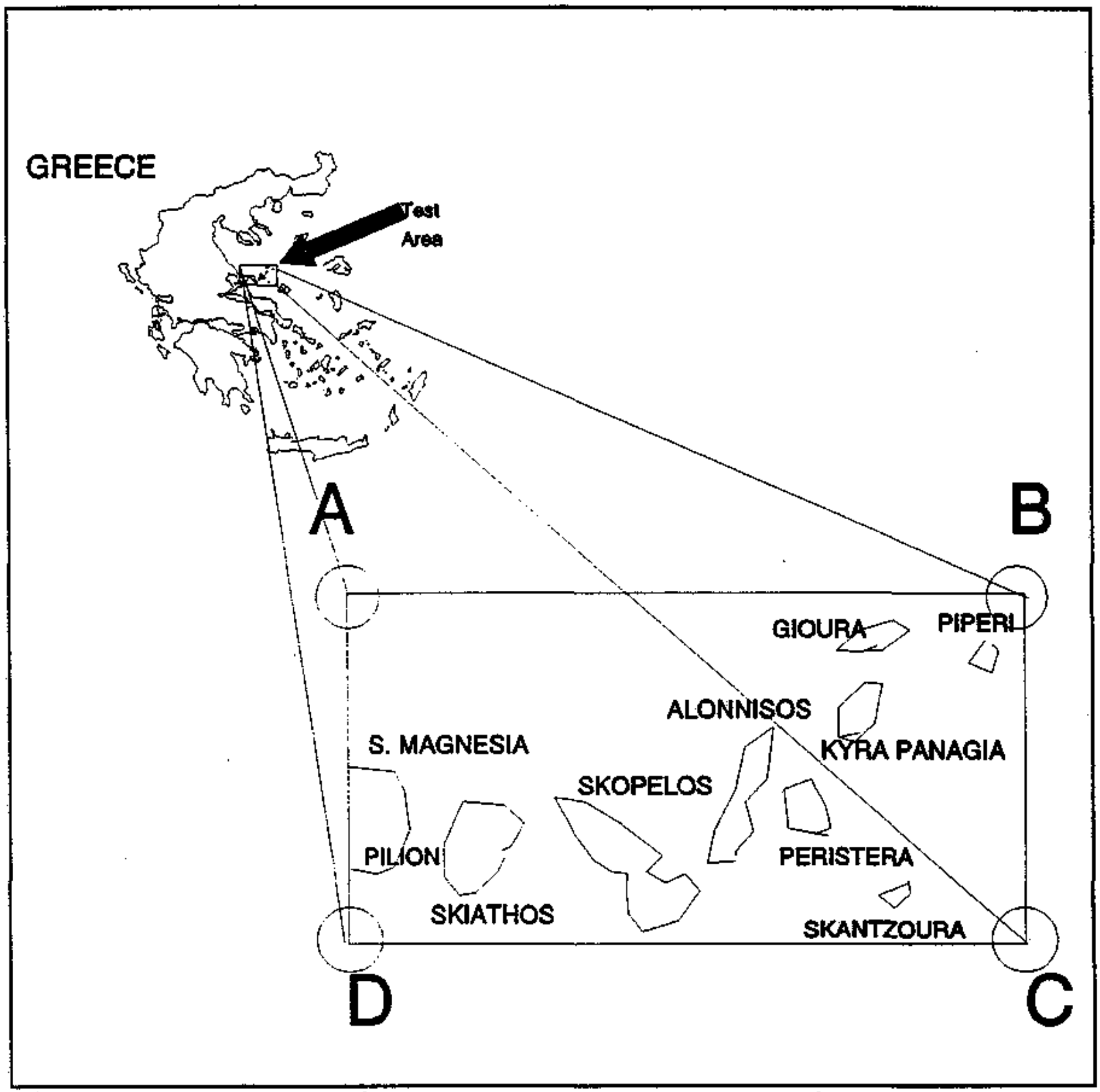

Figure 7: The location of the Northern Sporades test area.

been studied in Despotakis (1988 and 1991).

From the above discussion it becomes apparent that the SD conflicts on the study area are dynamic phenomena. Some of these conflicts can also be expressed directly in spatial dimensions (e.g., the expansion of urban land at the expense of forest areas). But it is only through the use of a spatio-temporal hybrid GIS-SD dynamic model, that we can satisfactorily approach and simulate the mechanics the various SD conflicts. For such a purpose, a meaningful policy model for this area should have the following features:

- it should focus on the dynamic simulation in space and time rather than being an optimization model (see Despotakis and Giaoutzi, 1990).
- it could assist researchers in examining the dynamic economic and ecological conflicts of our study area in their physical dimensions (three dimensions for spatial reference together with one dimension for dynamic reference over time).
- it would provide alternative strategic solutions by means of scenarios which should be based upon SD constraints for the development of the region.

Data requirements

The data requirements for such a GIS-SD hybrid model are determined by (1) the spatio-temporal resolutions selected (i.e., 100m x 100m ground pixel size, and a simulation period of 1 year), and (2) the data needs for a successful GIS-SD model calibration.

The data supply may not necessarily be in a one-to-one correspondence with the data demand. This means that (1) digital data may have been collected and processed which finally are not used as an input into the GIS-SD model, but rather form an integrated digital data base and (2) necessary digital data for the GIS-SD model may not have been available for the period the model was developed and tested. The data collection process focused mainly on obtaining as much information as possible about the socio-economic and natural environment of the study area.

In general, the necessary data input into both our GIS-SD model and the digital data base constructed, was designed to have the following data features:

Non-spatial data
- data on the socio-economic reality of the region (productivity and income per economic sector, tourism, fishery, houses, energy used per household, etc.)
- demographic data (population, age pyramid etc.)
- ecological data (ground water, sea water quality, forest fires, wild life data etc.)

Spatial data
- terrain elevation and sea depth data
- land use data
- distance data from important land uses such as urban land, forests etc.
- road transportation network data etc.

The combined SD-GIS model was mainly applied to the island of Alonnisos. After the necessary spatial and non-spatial data requirements were set, the relevant data were collected from the various (mainly Greek) sources: National Statistical Service, Greek Military Geographic Service, Ministry of Environment, Planning and Technical Works etc.

Based on the selected data, we ran our GIS-SD model as follows (see for more details Despotakis, 1991).

Two scenario runs - generated by successively excluding and including road transportation on Alonnisos island - were carried out to demonstrate the efficient use of our GIS-SD system for monitoring urban development under different urban attraction conditions. The attraction layers generated by our system are shown in Figures 8 and 9 for the case of "absence" and "presence" of transportation, respectively. Using these attraction layers we run our system for a simulation period of 15 years, starting with the year 1985, and ending with the year 2000, for every five years. The results are shown in Figures 10 and 11 for the case of "absence" and "presence" of transportation, correspondingly.

The effects on urban expansion which result by considering the road transportation as a spatial attraction network are clearly depicted in the above two figures: for the "no transportation" scenario the urban expansion takes place mainly across the sea shore and the already existing urban areas of the island; for the "transportation" scenario the urban expansion presents clusters spread along the roads of the island, thus eliminating the size of the urban area to be spread along

the sea shore. Our GIS-SD system provides these results in the form of raster images which may also be used for animation applications, so that more intuitive information may be extracted from the simulation results. These two scenario results can be inserted into a DSS as follows.
For each criterion (e.g., nature, tourism, etc.) an evaluation map is generated which corresponds to the selected alternative for a specific year. A weighted summation for each evaluation map may result in an unambiguous performance indicator. This number may then be inserted into its corresponding position in a plan effect table. Multi-criteria analysis (see, e.g., Janssen, 1991) may then be used to rank the selected alternatives. Using the above approach a transformation from a two-dimensional space to the one-dimensional space is carried out. Alternative methodologies may result in a rigorous two-dimensional DSS using multi-criteria analysis (see, e.g., Guariso and Werthner, 1989).

Figures 8, 9, 10, 11 about here

7. Outlook

The GIS-SD system described in this study mainly operates on raster data; at the present time, where economic-ecological procedures are spatially simulated by a GIS, the reduced spatial accuracy of rasters does not seem to create any problems. Since the topology is easily preserved and the spatial objects are well-defined with rasters, these factors make up for their limited spatial accuracy. In the future, other data structures may be tested such as the quadtree structures.
In general, the future developments of our system are mainly identified in the operationalization stage (Figure 12).
We provide here 7 proposed system future developments which may include among others:

1. Improved models: spatial and non-spatial models that are used to simulate the natural and socio-economic reality of a region are often based on assumptions; these assumptions may not be true, especially in the case of complex environmental models. Improved models are needed in order to overcome assumptions or "wild guesses" for specific processes.

2. Improved spatial analytical tools: although the non-spatial analysis offers a large number of potential analytical tools (time series analysis, stochastic and deterministic processes analysis etc.), the spatial analysis field, being a newly developed field, is still poor in spatial analysis tools. Improved spatial analysis tools may be derived by expanding the one-dimensional available tools to include two- or three-dimensional analysis.

3. Integration with remote sensing: the potential of the remote sensing satellite data resides in their capability of providing the researchers with (1) multispectral and (2) multitemporal raster data. These data may serve as additional data layers for the region under investigation.

4. Improved error analysis modules: an improved error analysis module which may operate in parallel with the whole GIS-SD system is necessary. Such a module would provide detailed information on the expected quality of the data and the model results. Then, in case we would like to increase the output quality, we would either collect more data or

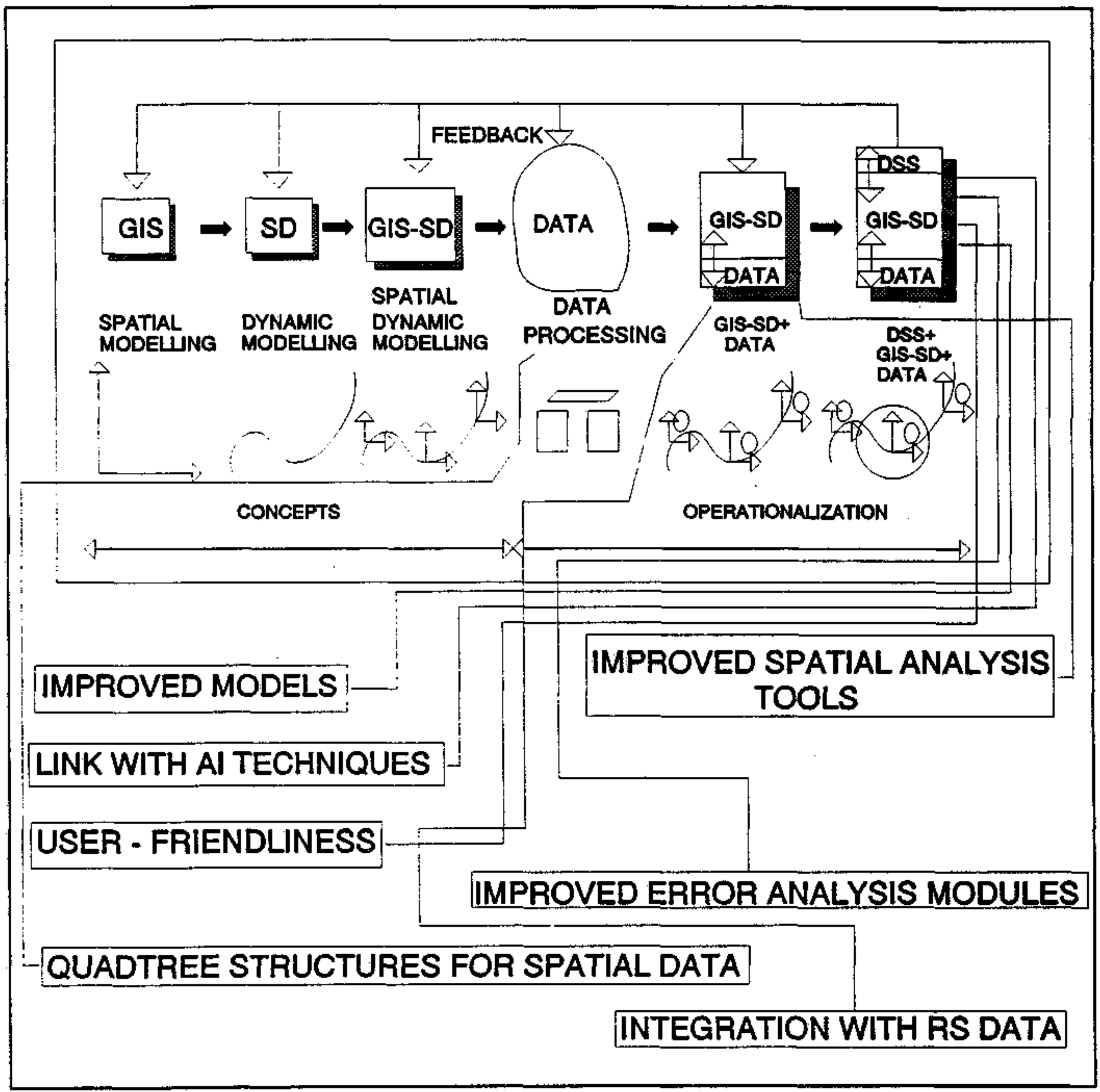

Figure 12: Plausible future developments for our GIS-SD-DSS system.

improve the models; in case the predicted quality was sufficient, we would proceed with the model simulation runs.

<u>5. Use of quadtree structures for spatial data:</u> the structures used in our study were mixed raster, vector and quadtree structures; the main layer-stock link within the dynamic simulation was carried out using raster layers. If all the layer operations between the original and derived spatial data are to be carried out in a quadtree mode, this will result in faster and more efficient computations throughout our system. Thus the raster structure (typical spatial structure for analyzing economic-ecological thematic data) may be substituted by the quadtree structure.

6. User-friendliness: making a complex system user-friendly clearly narrows its range of applications and makes the system more rigid. However, user-support tools is necessary to be provided together with the GIS-SD system.

7. Link with AI techniques: the recent advances in the field of AI technology, offer a new potential to be explored by a GIS. Especially in the field of spatial analysis, the new AI tools offer tremendous possibilities to be utilized. These include amongst others the utilization of neural networks (see, e.g., Openshaw, 1991), pattern recognition methods, group method data handling methods and genetic algorithms for analyzing GIS-SD fuzzy (input or output) information.

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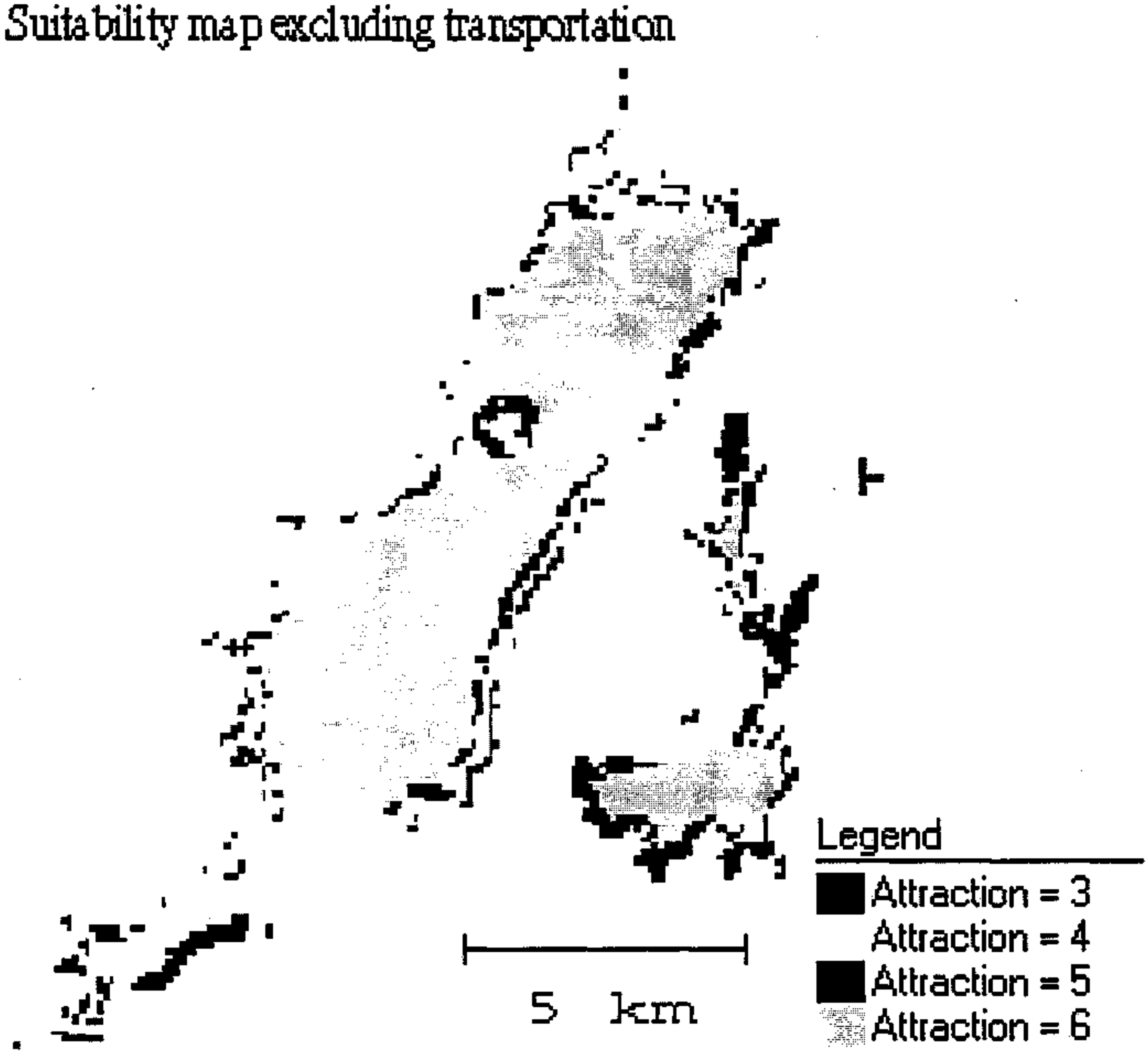

Figure 8: Suitability analysis excluding transportation in behaviourial scenarios.

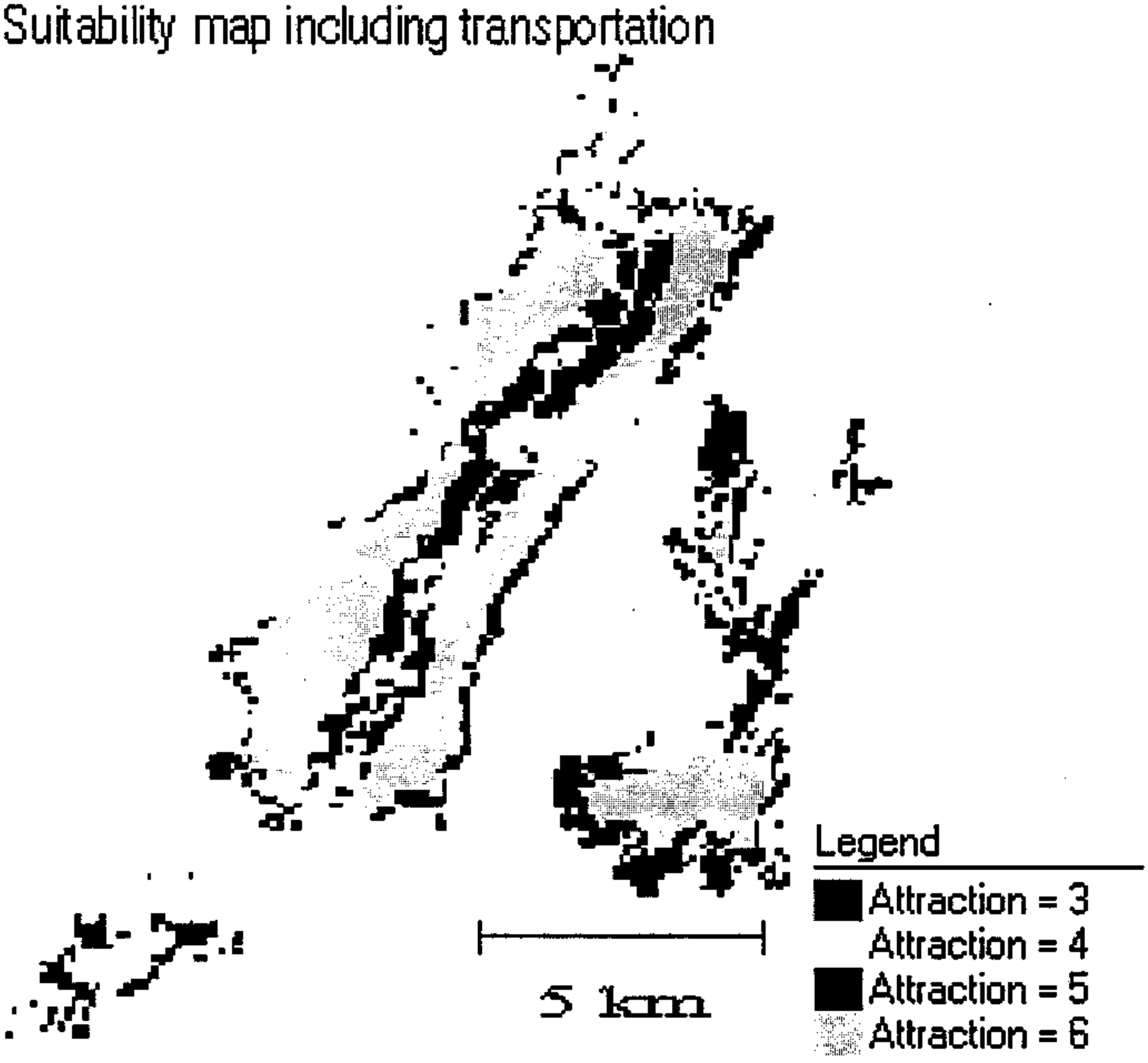

Figure 9: Suitability analysis including transportation in behavioural scenarios.

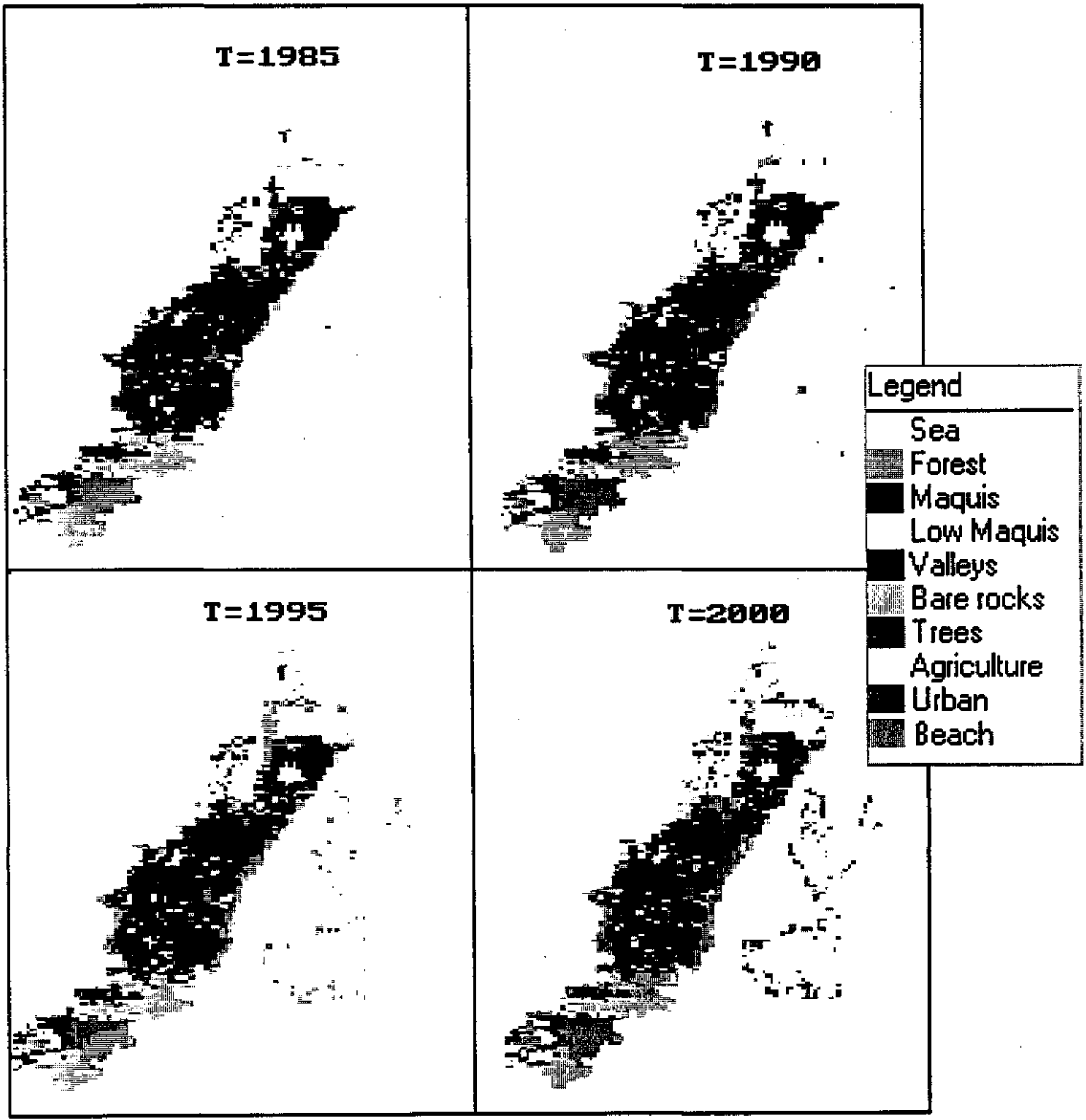

Figure 10: Dynamic land use changes for the "no transportation" scenario.

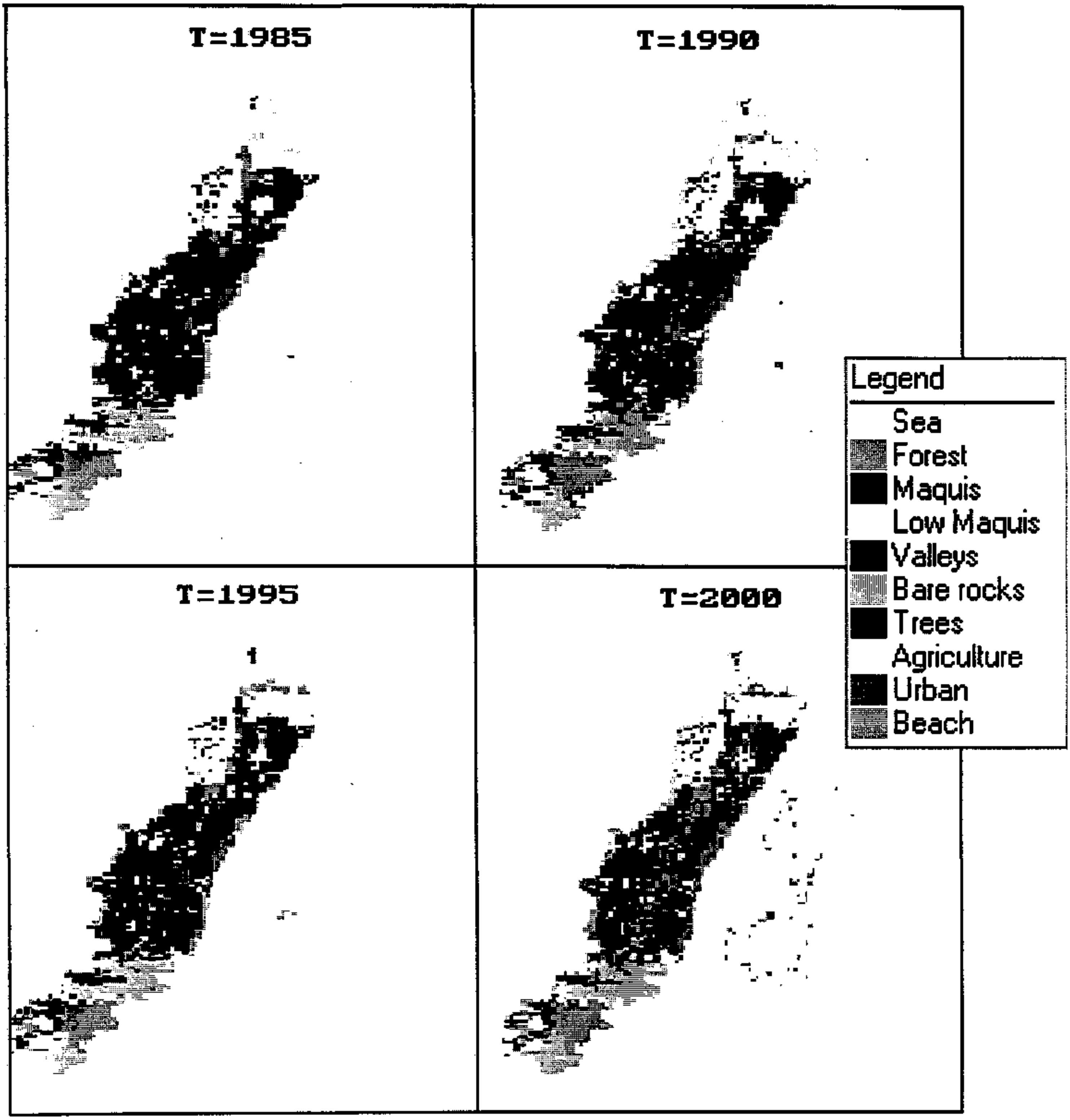

Figure 11: Dynamic land use changes for the "transportation" scenario.