CHAPTER FIFTEEN

Dynamic Modelling and Landscape Patterns – A GIS Synthesis

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15.1 INTRODUCTION

The multitude of environmental problems in a world of dynamic and unpredictable natural systems stimulates the need for new methods which make use of recent developments in the digital integration of data, dynamic models and human reasoning. The obvious spatial dependence in these systems suggests the application of geographic information systems. However, present GIS are designed for two-dimensional static data with low noise, and current models of earth surface processes have developed from non-spatial models often pertaining to oversimplified (i.e. scale-defined) cause/effect relationships and equilibrium theories (Gumbricht, 1996a). Nevertheless, models have features needed to solve complex problems; GIS have others. The coupling of GIS and models is therefore currently receiving much attention (Goodchild *et al.*, 1993). This chapter reviews recent developments in using GIS for modelling of earth surface processes. The objective is to initiate the development of a more robust approach towards sustainable landscape management in a fast-changing environment.

15.2 A CONCEPTUAL MODEL OF LANDSCAPE ORGANISATION

Landscape is a thermodynamic open system in which daily pulses of solar energy (with annual modulation) are dissipated through transport and reaction processes. Through this energy dissipation an ordered structure evolved – life. Through evolution, living structures closed matter flow into local cycles and decreased irreversible matter losses from the land surface to the sea. Life controls energy dissipation mainly through phase-related dialectic processes in the water cycle: photosynthesis and respiration, evapotranspiration and condensation, dissolution and crystallisation. In natural landscapes, maximum vegetation growth and thick raw humus layers lead to high biological control of the water cycle (Gumbricht, 1996a).

The processes of life are dependent on boundaries which envelop different functions.

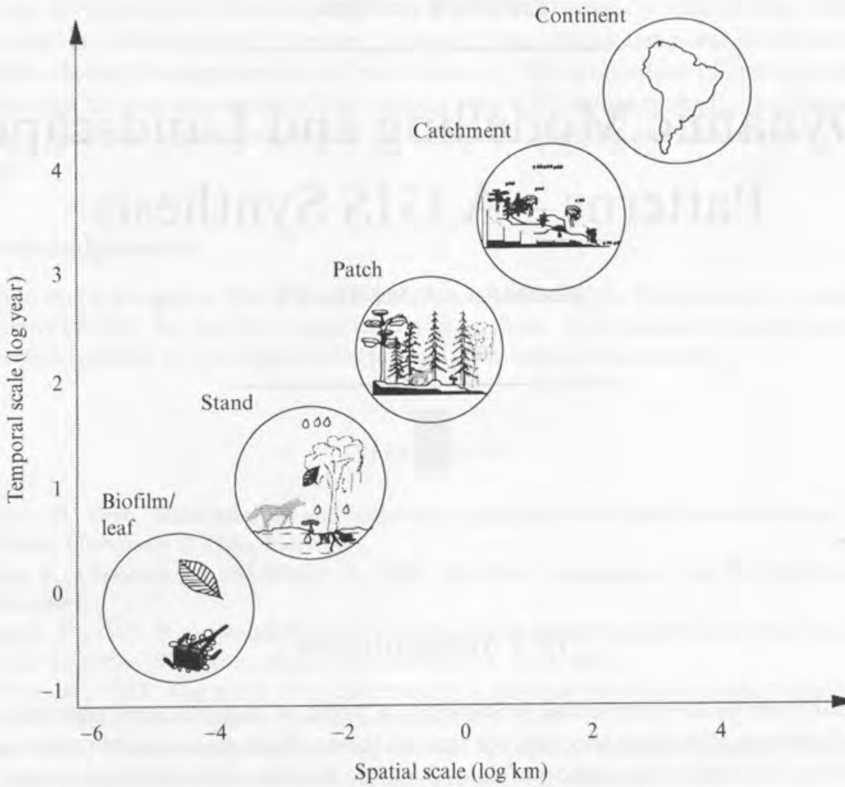

Figure 15.1 Hierarchical organisation of natural frequencies and quanta of energy dissipation. (From Gumbricht, 1996a.)

The boundaries have varying degrees of thermodynamic openness, with the capacity of creating and sustaining interior negative entropy as the most significant system character (i.e. to 'create order out of chaos' in the words of Prigogine and Stengers, 1984). Naturally bounded scales (or quanta) of the continuous hierarchy, suggested for instance by Holling (1992), include tree stand, patch and landscape (Figure 15.1).

With a few key species and related 'keystone processes' these quanta represent both spatial architectures and temporal frequencies ('landscape signals') attracting and entraining other species, processes and patterns. The quanta communicate via different (waterborne) signals up and down the scales. At any scale the receiving signal stream is interpreted via its interface (equivalent to a filter) and either processed in connected parallel structures or randomised owing to asymmetries (overconnection) or lack of interfaces (underconnection). The most important components of the landscape system are patches of different vegetation and their dynamic boundaries (synonyms are transition zones, ecotones). Thus a major task for the GIS community is to portray system (i.e. landscape) morphology in terms relevant for modelling system behaviour or dynamics.

With cultivation and urbanisation the landscape system is severely underconnected, leading to unprocessed signals (noise) escaping to and pertaining to other scales. These processes have become globally cumulative (Turner *et al.*, 1990) linking global change to regional flip-flop behaviour and local surprises (Holling, 1986). This

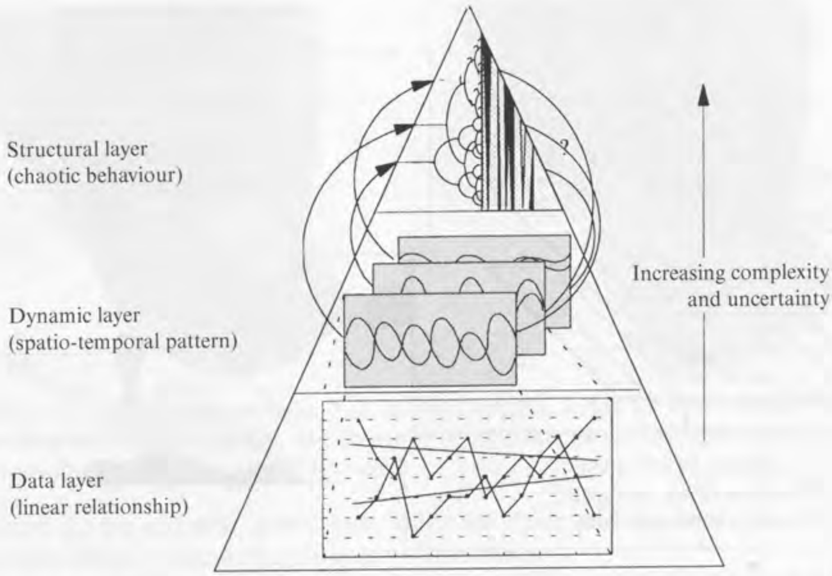

Figure 15.2 A three-layer perspective of data, dynamic processes and cybernetics for integrated modelling in GIS. (Free interpretation of Grossmann, 1991.)

chapter reviews the use of GIS for nesting these scales, for modelling and management, for scenario generation and for hypothesis testing.

15.3 MODELLING IN GIS

In environmental modelling the scale of the process under study and the parametrisation of the model used to distil the key features of that process are often biased. To overcome these problems Grossmann (1991) suggested a hierarchical three-layer perspective for modelling natural phenomena in GIS: a basic layer of data, a middle dynamic layer and a top strategic layer (Figure 15.2).

Models in general can have one of two aims: to improve the understanding of real-world processes or to forecast future events for improved decision making. Traditionally, models are defined as scaled, conceptual or mathematical, where the mathematical models have the widest use in environmental modelling. Mathematical models can be further classified as deterministic or stochastic. Both deterministic and stochastic models can be either steady-state (time-invariant) or dynamic (time-variant). Models in GIS obviously have a spatial dimension (i.e. a computational element smaller than the scale of the process being studied), and are thus said to be distributed (or semi-distributed) as opposed to being lumped over large regions. There is a trend away from lumped models towards models favouring distributed parameters with physical interpretability (e.g. Hay *et al.*, 1993; Moore *et al.*, 1993). Part of the drive behind this development has been the belief that the sequential task of dividing a landscape into smaller units permits the prediction of non-linearities and spatial variability. However, the landscape reveals more information at higher spatial resolution, apparently without limit (cf. Mandelbrot, 1982). It can be argued that distributed models are also lumped, albeit on a grid scale (see, for

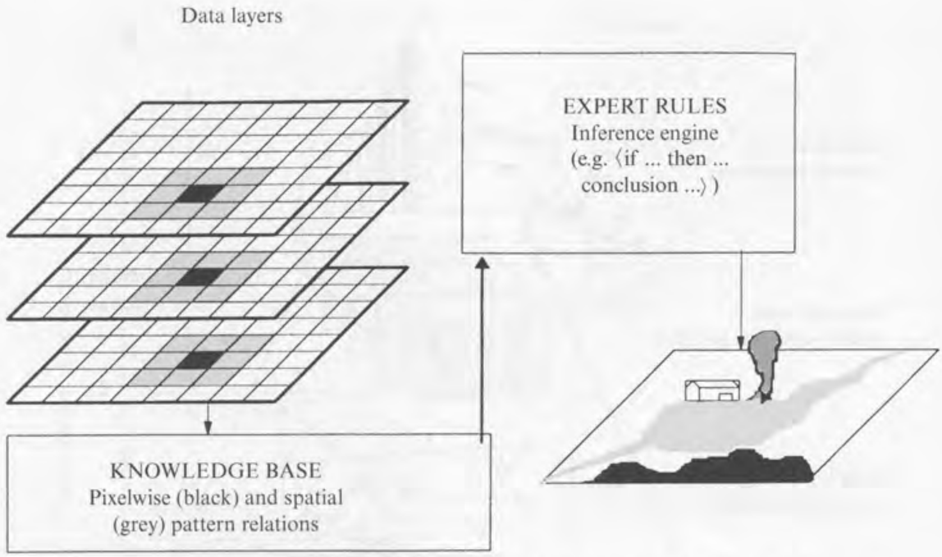

Figure 15.3 Schematic structure of an expert system for spatial data modelling.

example, Beven, 1989). Alternative approaches based on subgrid parametrisation using synoptic indicators and higher statistical moments have been suggested by Avissar (1993), Moore *et al.* (1993) and Gumbricht (1996a), among others. This approach surrenders to the difficulties associated with a mathematical representation of large-scale processes in complex environments with the effect that transparency, simplicity and full spatial distribution are emphasised at the expense of physical sophistication.

15.4 LANDSCAPE MORPHOLOGY AND DATA STRUCTURES IN GIS

The data in GIS represent either 'fields' (for example elevation, groundwater level, soil class, spectral reflectance) or discretised 'object' classes (for example lakes, cities, states). Most natural phenomena are of field character, whereas anthropogenic structures and definitions usually are object-oriented (Goodchild, 1993). In GIS, data can be represented in the form of either raster cells (or rectangular picture elements or pixels) or vectors (Goodchild, 1993). Object data are naturally vector-related with present developments being towards fuzzy encapsulation, inheritance and identification (cf. Worboys, 1994). However, both formats are increasingly integrated into software packages.

Field data in raster format (i.e. satellite imagery) often need to be converted to objects (or image regions) for communication to the user. Traditional data modelling from remotely sensed imagery is based on pixelwise statistical rules relating ground objects to spectral reflectance in different wavebands (Argialas and Harlow, 1990). A present development is to use non-statistical (qualitative) relations inferred via expert rules (Figure 15.3).

Such relations can also be stated for spatial patterns. Gumbricht *et al.* (1995) developed a forward-driven contextual post classifier for patch-ecotone landscape classification. Information from *a priori* classified cells are used together with spatial

Figure 15.4 Cartographic modelling of (a) the DRASTIC index for groundwater pollution potential of the Managua aquifer, and (b) a map of suitability for well location based on multi-criteria evaluation using the DRASTIC index.

variation in, for example, a leaf-area index for distinguishing between pixels with mixed classes and those with unique transition zones.

Expert systems can be both backward (goal) and forward (model and data) chaining and have previously been rather complex in structure and designed for data sets with low noise. The trend has been to create easy-to-use systems with procedural logic based on natural language in which the user specifies *how* it should be done (Wang, 1994). This more inductive approach is now also making use of the concept of neural networks (for example, Civco, 1993). Another recent approach has been towards compact transparent rules and fuzzy membership functions (for example, Leung and Leung, 1993; Dymond and Luckman, 1994). Using direct rule structuring, or declarative logic (the user specifies *what* is required) for hypothesis testing and manual updating has been less strong (for example, Chmiel and Gumbricht, 1996). Apart from software development it also demands domain knowledge and experience.

The development in data modelling and data integration is leading to better morphological models of the landscape at different scales – a prerequisite for many modelling purposes.

15.5 CARTOGRAPHIC MODELLING

Rooted in the overlay of transparent maps (for example, McHarg, 1969), Tomlin (1990) and Berry (1993), among others, developed cartographic modelling and map algebra. Early applications include vulnerability assessment of groundwater by the DRASTIC method (Depth to groundwater, Recharge, Aquifer media, Soil, Topography, Impact of vadoze zone, Conductivity) where each of the seven factors i has a physically related value x_i in each position, and a predefined weight w_i, with vulnerability calculated as $\sum_i x_i w_i$ (Gumbricht, 1996c). Risk evaluations (for example of salt water intrusion, see Lindberg *et al.*, 1996), and identification of source areas (for example of diffuse pollutants, see Sivertun *et al.*, 1988; Tim and Jolly, 1994) are other common examples. Figure 15.4 shows examples of maps of the DRASTIC index and illustrates how overlaid images can be used for decision support, in this case for finding suitable well sites in the Managua aquifer based on multi-criteria evaluation (see Carver, 1991; Gumbricht *et al.*, 1996a). Groundwater recharge, groundwater yield

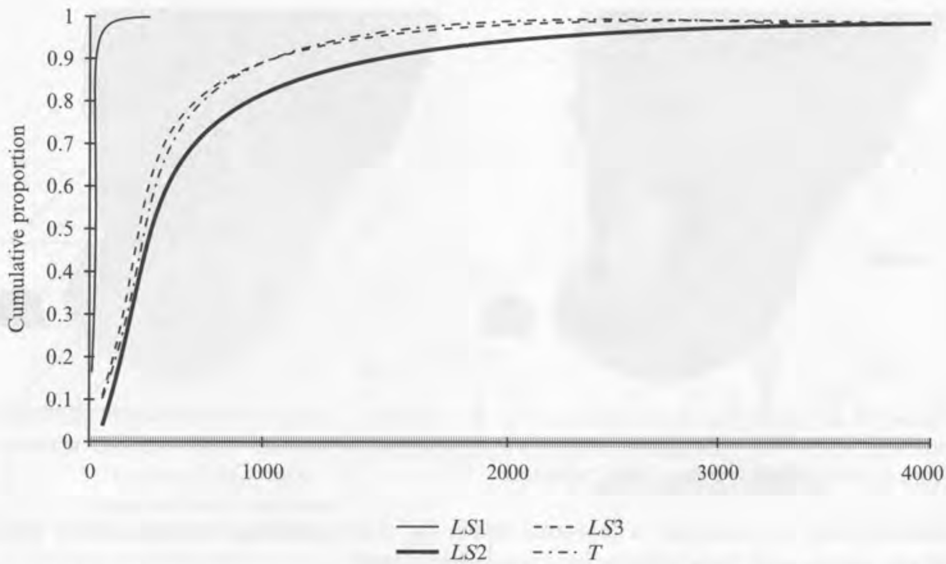

Figure 15.5 Water transport capacity for a 1 km^2 area in Cyprus calculated as the *LS* factor of USLE (as given in Desmet and Govers, 1994) and the *T* factor suggested by Moore and Burch (1986). (From Stenström and Gumbricht, 1997.)

and proximity to pollution sources as decision factors were each given an equal weight, and each position ranked between 0 and 255 for each factor. Light shading corresponds to high pollution potential and suitability, respectively; black is water.

Cartographic modelling and integrated data from GIS and remote sensing are now commonly used for parametrising both physical and empirical models of for instance hydrology and erosion (Pilesjö, 1992; Maidment, 1993; Wilson and Lorang, this volume, Chapter 6). Digital elevation models can be used as a minimum data set in hydrological modelling with the simplifying assumption that the upstream area can represent the amount of water passing a cell or point. The empirical algorithms for antecedent soil moisture conditions suggested by Beven and Kirkby (1979) and O'Loughlin (1981, 1986), and indices of slope length and transport capacity have been especially useful in modelling surface and near-surface hydrology and erosion.

The Universal Soil Loss Equation (USLE) and its derivatives provide perhaps the widest example of a loose coupling of an empirical, additive model to GIS. As pointed out by, for example, Wilson and Lorang (this volume, Chapter 6), the lack of consensus and transparency in such models causes problems, especially when applied at new sites, using data of unknown quality. Figure 15.5 shows the derivation of the length-slope factors of the USLE and its sensitivity to resolution, accuracy and algorithms used.

The *T* factor and *LS*1 were calculated from a digital elevation model (DEM) of 10 m resolution generated from maps in the scale 1:5000. The *LS*2 and *LS*3 curves were calculated from a DEM with 50 m resolution generated from maps in the scale 1:50 000. *LS*2 is the original DEM, and *LS*3 carries an error term equal to the standard deviation of the difference between the two DEMs.

Such problems have directed GIS integration from empirical to more elaborate models based on simplifications of governing physical laws (for example, of mass and momentum).

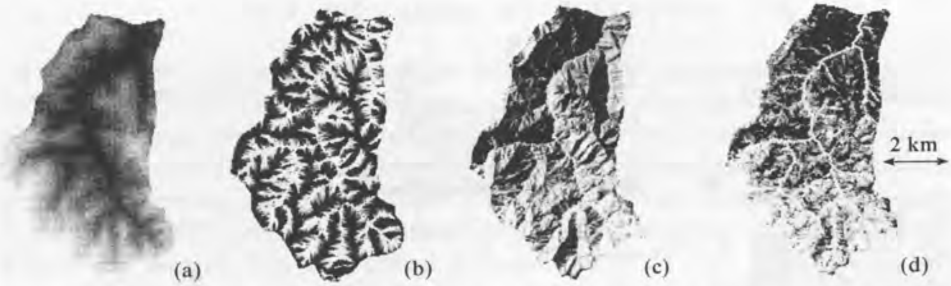

Figure 15.6 A watershed on a forested slope in Cyprus displayed as (a) digital terrain model, (b) upslope drainage areas, (c) wetness index, and (d) estimation of leaf area index. Light shading corresponds to high values in all images. (From McCarthy, 1996, with permission.)

Comparing different maps and their pattern similarity using heuristic methods and simple statistics (for example, of mean and standard deviation) is one of the more promising approaches in understanding cumulative process-pattern relations in the landscape (cf. Gumbricht *et al.*, 1997b). Figure 15.6 shows high spatial resolution temperature and wetness indices derived from satellite data (Landsat TM, calculated as given in McCarthy, 1996), and a digital terrain model displayed as elevation and 'updrain' area (calculated by the formula presented by Quinn *et al.* (1991) as given in Desmet and Govers, 1994).

The patterns appear similar, but statistical relations are poor (McCarthy, 1996), which is attributed to problems in position accuracy and choice of algorithms.

15.6 REPRESENTATION OF DYNAMICS IN GIS

Dynamic processes can be coupled to GIS either as a superimposed function over the whole study area ('dynamic maps'; see Grossmann and Eberhardt, 1992), or as an area dynamics dependent on site-specific and topological relations. The dynamic map approach is commonly used for nesting large scale models (for example, global circulation models for climate scenarios; see Lee *et al.*, 1993; Hay *et al.*, 1993) with smaller-scale models of hydrology (Nemani *et al.*, 1993) and ecology (Schimel and Burke, 1993). The smaller-scale models can in turn be used to generate area dynamic processes for subgrid parametrisation of the larger-scale models (see, for example, Lee *et al.*, 1993; Moore *et al.*, 1993; Avissar, 1993). Most of the models use the Leaf Area Index (LAI – defined as the leaf area per unit ground area) as an important parameter relating to stomata processes (cf. Figure 15.6).

The strongest development in using GIS has been for parametrising distributed models for creating and selecting regions with similar behaviour (for example, of hydrological response units, HRU; see Flügel, 1996) and for displaying model input and output. This approach places less demand on the model developers and programmers but is flexible for those who master GIS (see Fedra, 1993). In most cases GIS is used as a static tool for map algebra when interfacing dynamic models.

The present development is towards sharing GIS data formats in an intermediate coupling (Ehlers *et al.*, 1991; Tim and Jolly, 1994). This is a common approach in more physical models of erosion (Wilson and Lorang, this volume, Chapter 6), surface hydrology (Maidment, 1993) or groundwater flow and transport (Gumbricht and Thunvik, 1996). The most advanced coupling should be seamless, with the model

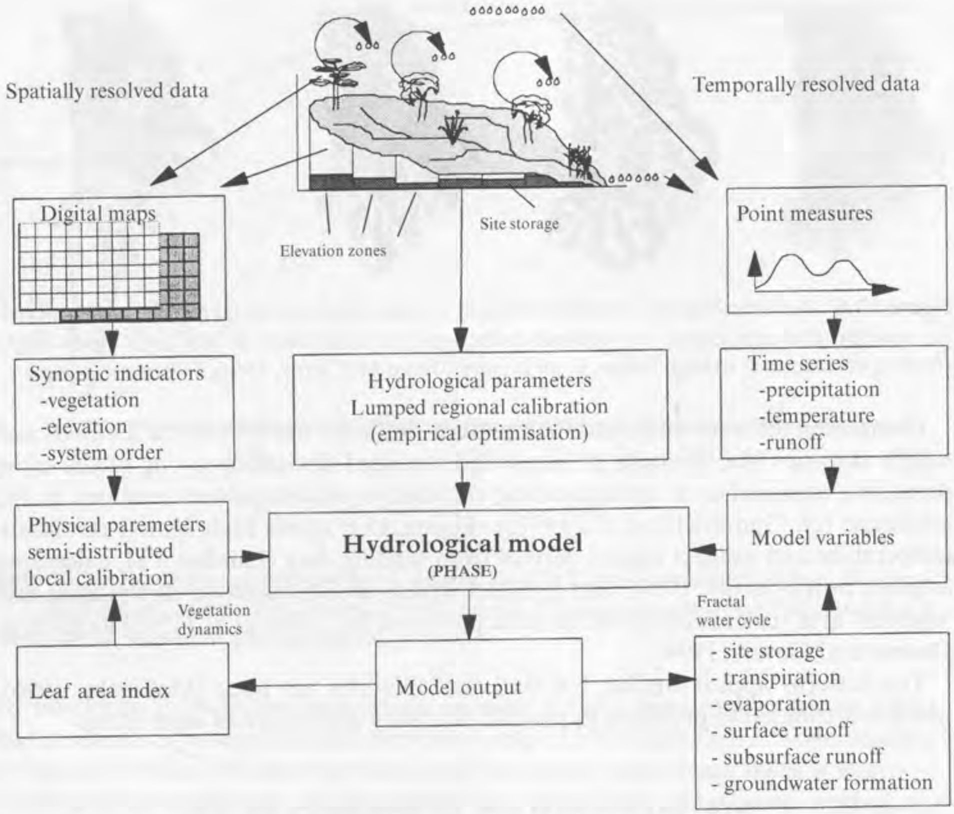

Figure 15.7 Schematic relation of landscape spatial structure and hydrological functions as interpreted in the PHASE model. (From Gumbricht, 1996b.)

embedded in (or embedding) a GIS. Operative examples include the hydrological SHE model (Abbot *et al.*, 1986) and the LISEM erosion model (De Roo *et al.*, 1996), both based on simplifications of the laws of mass and momentum. However, as small-scale phenomena are averaged over larger regions, conceptual models often perform as well as the more elaborate models. This has fostered new approaches of subgrid parametrisation and semi-distributed models. Figure 15.7 shows the principles of a system hydrological model (PHASE) developed by Gumbricht (1996b) and its coupling to GIS for subgrid parametrisation (in this case of elevation zones).

The model is regionally calibrated by lumped hydrological parameters for soil moisture accounting and routing. Local calibration is based on semi-distributed physical parameters derived from GIS and remote sensing. Dynamic feedback processes can be introduced by a simple vegetation growth and decay function, and by a fractal water cycle. The model emphasises the reciprocity between vegetation dynamics and the water cycle. Regional calibration is based on optimisation. The model is locally parametrised by GIS and remotely sensed synoptic indicators of the landscape structure. This is a simplification of the underlying physical processes with the focus on key factors modulating system behaviour. The model has shown robustness in transferability in parameter settings when applied to data of Cyprus (Gumbricht *et al.*, 1996b) and the Himalayas (Gumbricht *et al.*, 1997a).

15.7 DISCUSSION AND CONCLUSION

At a landscape scale, water is the major formative agent, inextricably linked to patterns of relief, geomorphology and vegetation. Water is a key element in environmental regulation as energy absorber, as unique solvent, and as raw material in photosynthesis. Dynamic water (energy) processes and interactions form a non-randomly distributed hierarchical system in space and time. Landscape morphology is reciprocally linked to these processes, and landscape modelling and classifying should benefit from taking their starting point in such key relations.

Several studies have concluded that GIS could help in specifying spatially varying parameters for improved modelling based on the present model formulations. However, generating distributed data from point and line data often leads to GIGO (garbage in, garbage out), with a large risk of seducing the user into a false feeling of model accuracy (Fedra, 1993; Grayson *et al*., 1993). When extracting secondary parameters from such data the result can be surprisingly different dependent on scale, algorithm and small data errors. The problems of poorly understood data and disregard of error and scale effects easily lead to wrong conclusions, and in the worst case, management actions mitigating their intentions. GIS data should carry a quality tag. Models need to be developed with greater care; they should be parsimonious in their data consumption, and used with modesty when applied to new conditions or outside their scope. The ease with which data sets are created and manipulated in GIS easily fools the user to overstep these rules.

It is concluded that much of the present elaborated work on coupling or integrating advanced models with spatial data is premature; models are site-specific and causative, GIS are static and two-dimensional. GIS should instead be used for hypothesis testing and more robust model building through taking an initial step back and re-emphasising heuristic pattern recognition methods. A suggested working scheme for the further development is sketched in Figure 15.8.

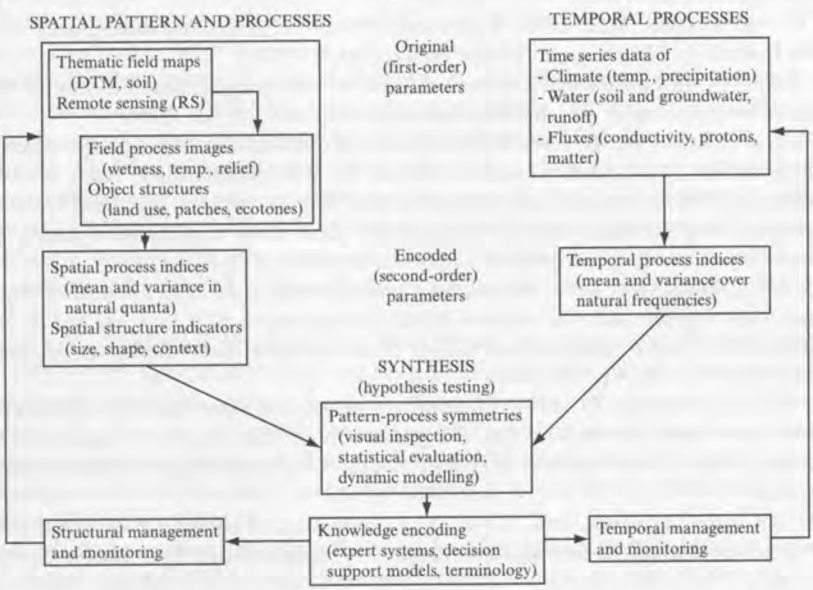

Figure 15.8 A proposed methodology for the development of robust tools for sustainable management. (From Gumbricht, 1996a.)

A deeper integration demands a more modular and transparent approach. GIS can assist in bridging different spatial scales by subgrid parametrisation based on, for example, higher statistical moments. The relation between spatial and temporal processes can be evaluated by synoptic, logical and transparent indices derived from GIS.

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