Modelling water and vegetation reciprocity
-a landscape synthesis in GIS

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"The only constants are functions - exchanges as Heracleitus said, connections as E. Mach expressed it. Nothing exists by itself or in itself. Everything exists through reciprocity, 'Wechselwirkung'" (Boodin, 1943, quoted in Allen and Starr, 1982).

PREFACE

The thesis stems from a holistic tradition in landscape studies, of which I have become increasingly aware during the ten years that have emerged since I started my work. As the study is related to many fields of science, it took me longer than expected to finish it. I dedicate the thesis to all my students that I have taught during eight years at the Royal Institute of Technology (KTH), especially those who became friends. Most of the information I sought, I needed for our dialogue. All the major sites used, Cyprus, the Himalayas, and the Great Mazurian Lake District in Poland, have been subjects of MSc degree projects which I have supervised. Apart from the students having undertaken those projects, Jerzy Chmiel (doctoral student), Robert Szczepanek, Jenny McCarthy, Camilla Mahlander, Piotr Bernatek, Bartlomeij Wazniewiscz, Martin Hessling, Henrik Lindholm and Anders Åkre, two other students chose me as their supervisor, Elisabeth Carlsson and Hans Jacobson, and were equally important for the successful fulfilment of this thesis. Many thanks to my supervisors, Dr Jan-Erik Gustafsson and prof Gert Knutsson. My deepest gratitude to prof Wilhelm Ripl (TU Berlin), whose ideas have coloured my research, and who became a friend of mine.

ABSTRACT

In natural landscapes life uses solar energy to control the water cycle and creates a stable environment, coherent with locally closed matter cycles and high gross productivity. With human interference, natural stable conditions mostly are severely affected; the process of tightening, pollution free biogeochemical cycles pertaining to ecological development is reversed. In the highly non-linear biosphere system transient changes on one scale can trigger chaotic behaviour and unpredictable changes on other scales. The present development is unsustainable. The aim of the thesis has been to create a concept and a set of tools applicable for robust sustainable management in a transient environment. The focus of the study is the landscape scale. The study is based on data from Cyprus, the Himalayas, Poland and Sweden. It includes the development of a Geographic Information System (GIS) integrated rule based expert system incorporating fuzzy logic for landscape classification. Transparency and ease of use makes the system a powerful tool for inferring knowledge relations, and hypothesis testing. Emphasising the reciprocity between the water cycle and vegetation, a GIS-coupled hydrological model was also developed. The model is regionally calibrated using a few empirically optimised parameters, with physically based key indicators of vegetation, size and elevation automatically extracted from GIS and remotely sensed data when applied to a specific basin. The model could successfully forecast runoff when transferred between different catchments, as well as in independent periods. The model was also used for evaluating carbon dioxide induced climate changes, including subsequent vegetation responses. The general conclusion of decreased runoff and of larger soil moisture deficits was confirmed, but model results showed that the magnitudes of change are highly unpredictable. The overall conclusion is that the landscape pattern is a reciprocal manifestation of dialectic processes in the water cycle, regulated by life when present. System non-linearities and feedback loops forges a step back in modelling, and favour the development of simple and transparent models applicable for public participation, as well as policy and management decisions.

Keywords: hydrology, ecology, sustainable development, system analysis, geographic information system, remote sensing, Cyprus, Himalayas, Mazurian.

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LIST OF PAPERS

The thesis is based on the following papers, which are referred to in the dissertation by their respective Roman numerals. The graphics and fonts of the original articles, and the printing process, demanded that the pre-published articles were redrawn. Thus all articles have been restructured instead of just reprinted in their original form. The article formats are however differing, reflecting the different standards of the journals where they were accepted/published. Minor spelling mistakes and reference lists have been updated (i.e. manuscripts referred to in published articles and published since the printing have been given in full). Paper VI have been more thoroughly updated.

I Ripl, W. and T. Gumbricht, 1996. Integrating landscape structure and water processes. Presented at Stockholm Water Symposium 1995, accepted for publication in Ambio.[1]

II Chmiel, J. and T. Gumbricht, 1996. Knowledge based classification of landscape objects combining satellite and ancillary data. In: K. Kraus and P. Waldhäusl (Eds.), International Archives of Photogrammetry and Remote Sensing, Vol. XXXI, part B4, pp. 183-187, Vienna.[2]

III Gumbricht, T., J. McCarthy and C. Mahlander, 1996. Digital interpretation and management of land cover - a case study of Cyprus. Ecological Engineering, 6 :273-279[3] [*]

IV Gumbricht, T., 1996. Landscape interfaces and transparency to hydrological functions. In: K. Kovar and P. Nachtnebel (Eds.), HydroGIS '96. Application of Geographic Information Systems in Hydrology and Water Resources Management. IAHS Publ. No. 235, pp. 115-121.[#]

V Gumbricht, T., H. Lindholm, A. Åkre, R. Szczepanek, M Hessling and J. McCarthy, 1996. GIS-integrated, fuzzy modelling of land surface pattern and processes in a Himalayan basin. Accepted for publication in International Journal of Water Resources Development.[4]

VI Gumbricht, T., 1996. Hydroclimatic processes and spatiotemporal landscape patterns. In: O. Sigurdsson, K. Einarsson and H. Adalsteinsson (Eds), Nordic Hydrological Conference, NHP-Report No. 40, pp. 360-368.

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INTRODUCTION

Hitherto environmental problems like contamination, acidification, eutrophication, desertification and climate change have largely been treated as isolated cause-effect problems; "basic scientific knowledge is typically fragmented into little islands of near conformity surrounded by interdisciplinary oceans of ignorance" (Ziman, 1996, p. 752). Solving environmental problems forges a holistic system perspective, and recognition of the complexity of natural phenomena (Clark, 1986; Wiman, 1991). The thesis attempts to demonstrate that environmental problems are inextricably connected to the water cycle. Water and its pathways over and through the landscape plays the dominating role in regulating the physical and chemical conditions of the environment, and in structuring the landscape morphology. Environmental (notably hydrological) modelling must thus integrate different landscape functions, including those of water, soil, ecosystem and climate.

Sustainability is suggestively defined as the longevity of the system under study (Costanza, 1996)[5]. A system with high internalisation of matter flows (or biogeochemical cycles) has a high thermodynamic efficiency. They preserve essential nutrients and minerals in ordered structures over time and space. Through energy dissipation in the thermodynamic open landscape, life evolved as a dissipative structure (Prigogine, 1980), controlling the flows of matter. The natural system is thus neither a small number causative system, nor a stochastic large number system, but a "middle number system" with self-organised complexity (Weinberg, 1975; Miller, 1978). Communication in this middle number system is reciprocal, and determined by a nested hierarchy of interfaces, reaching from planetary to microbal scales. Signals escaping processing lead to noise and perturbations at other scales. In a given spatiotemporal domain the distribution of interfaces and their symmetry with receiving signals will thus determine system efficiency and sustainability. Modelling or managing must take its starting point in the phase related spatial and temporal configurations of communicating components (Forman, 1990; Holland *et al.*, 1991; Hansen and di Castri, 1992; Ripl, 1995, Gumbricht *et al.*, 1996a).

The core of the thesis is a conceptual integration of the formative water processes and the intelligible features that compose the landscape (e.g. forests, fields, lakes etc.). Geographic Information Systems (GIS)[6] and Remote Sensing are used for identification, encoding and modelling of system morphology and dynamics. The aim has been to create a concept and a set of tools applicable for robust sustainable management in a transient environment.

BACKGROUND

Throughout the 19th century geographers and naturalists emphasised holistic approaches, and studied symmetries in species and landscape pattern distributions (e.g. von Humboldt, Candolle, Warming) (O'Neill *et al.*, 1986; Schreiber, 1989; Zonneveld, 1989). Von Humboldt defined the landscape as "the total character of a patch of the Earth" (translated in Zonneveld, 1989). The landscape patterns were linked to regional and global climate, which led to a static view of the natural world, in line with the ancient concept "Balance of Nature" (synonym: "Nature Benign") (Wiman, 1990). The close relationship between landscape patterns and processes was identified by Troll in the 1930's when studying aerial photographs and the ecological theories of Tansley. In the 1940's Watts developed an early concept of dynamic vegetation patterns (in space) and processes (in time), re-emphasised later by for instance MacArthur (e.g. in his equilibrium theories of island-biogeography), and elaborated by amongst others Bormann and Likens (1979), and White (1979).

Already in the 1920's Lotka introduced thermodynamics to ecology, and outlined the modern view of ecosystems as non-linear systems[7]. Lotka's work contributed to the understanding of the close links between the organic and inorganic worlds, and the concept of biogeochemical cycles through the work of Vernadsky[8] and Hutchinson in the 1940's. The cybernetic[9] character of ecosystems was concomitantly refined by Lindemann with his concept of trophic levels. Studies of flow of energy through ecosystems followed Lindemann and Lotka, and the functional (thermodynamic) perspective of life as a "negative entropy"[10] put forward by Schrödinger (1945). This led to the hypothesis of food chains (webs) and ecosystem energetics (notably H.T. Odum - e.g. 1971, 1983)[11], and of ecosystems as carefully controlling their own environment and function (e.g. O'Neill *et al.*, 1986; E.P. Odum, 1993). Ensuing discussion on autogenic[12] and allogenic[13] steering of ecosystems and their development consolidated into the hypothesis of ecosystem development leading to successive closure of energy and matter cycles to local sites (E.P. Odum, 1971), supported by many field investigations (e.g. Bormann and Likens, 1979, Picket and White, 1985). Alluding theories are the biomass increment hypothesis, postulating also the importance of the forest floor in tightening the cycles in the aggrading forest[14] (e.g. Covington, 1982; Vitousek, 1985), and the theory of ecological stability being composed of resistance (inertia towards disturbance) and resilience (ability to return to an equilibrium after disturbance) (e.g. Holling, 1973; Webster *et al.*, 1975)[15]. Holling (1986) developed a more dynamic view of ecological stability. He emphasised sequential interactions of four ecosystem functions: exploitation, conservation, creative destructionism, and renewal[16]. Acknowledging the importance of scale as well as non-biotic forces, Karr (e.g. 1996) expanded the concept to what he calls ecological integrity.

Landscape ecology

Initiated by Troll, geography and biology have merged in the heterogeneous discipline of landscape ecology (Forman and Godron, 1986; Zonneveld and Forman, 1989; Naveh and Liebermann, 1994). The holistic approach has been strong in a European descriptive school (Schreiber, 1989; Zonneveld, 1989)[17], whereas the recent introduction in North America has led to a more analytical school (Forman and Godron, 1986). The definitions and terminology in landscape ecology are, due to its heterogeneity and different schools, somewhat disparate. The smallest landscape study unit is the ecotope, or the biogeocoenose[18;19], a word stemming from the European tradition. The topology (geometric relationship) of the biogeocoenoses in a landscape, and their change and communication over time, define different subfields of landscape ecology (Zonneveld, 1989). The thesis deals specifically with classification, morphology (the structure and its elements), chorology[20] (spatial patterns and changes), and chronology (temporal variation). It follows the recent development of using GIS and Remote Sensing in such studies (Turner and Gardner, 1990; Goodchild *et al*., 1993; Haines-Young *et al*., 1993). However, the focus is on the water cycle and its relation to the landscape.

The water cycle

That the terrestrial hydrological cycle is driven by precipitation and connected to the land surface and its relief was first recognised by Perrault, who in 1674 published a study of the water budget of the river Seine. The central precept of hydrology that has emerged since then is that precipitation is a stochastic process controlling the hydrograph; gravitation creates a unidirectional flow route, with soil conditions dividing water between evapotranspiration, runoff and groundwater recharge (see Gumbricht, 1992a). The natural unit of the continental phase of the hydrological cycle is thus the river basin (synonyms: drainage basin, catchment, US: watershed), defined as the tract of land drained of both surface runoff and groundwater discharge by a given stream. Early concepts postulated that exceeded infiltration capacity generated storm runoff by saturated surface flow during precipitation (Horton, 1933), later supposed to be bound to lower slope positions (Betson, 1964), notably concave (Dunne and Black, 1970a and b). Following an early counterpoint in hydrology (e.g. Lowdermilk, 1933; Hoover and Hurch, 1944; Hewlett and Hibbert, 1963), research has emphasised the active role of groundwater[21]; initially for forming expanding saturated areas in lower slope positions generating saturated surface flow - *the variable source area* concept (Troendle, 1985). Recently the *transmissivity feedback hypothesis* of groundwater transiently raising into layers of higher conductivity (e.g. Lundin, 1982; Espeby, 1989) has gained wide acceptance in temperate regions as the runoff generation mechanism in undisturbed soils (e.g. Bishop, 1991). It is widely supported by natural tracer studies in the stream (e.g. Dincer *et al*., 1970; Sklash and Farwolden, 1979; Rodhe, 1981), showing pre-event water dominating even snow melt and storm runoff. The hill-slope distribution of recharge and discharge areas (see below), as determined by the relief, is emphasised for explaining antecedent moisture distribution and rainfall-runoff response (Troendle, 1985). The hypothesis is still challenged by the original Hortonian concept in arid climates and on disturbed land (e.g. Yair and Lavee, 1985; Dunne and Aubry, 1986). Most rainfall-runoff hypotheses have thus focused on soil and relief, and largely neglected the role of vegetation (for reviews see e.g. Dunne, 1978; Kirkby, 1988). Land cover/use and landscape patterns do however strongly influence atmospheric boundary layer structures and micro to meso scale circulation, as well as precipitation, runoff and water quality conditions.

Energy dissipation in the thermodynamic open landscape is very different on vegetated and non-vegetated land and wet and dry land respectively (Peschke *et al.*, 1991). Avissar (1993a) and Collins and Avissar (1994) used the Fourier Amplitude Sensitivity Test (FAST) to investigate land surface parameters related to energy dissipation in hydroclimatological models. They found surface roughness and plant stomatal conductance most important in densely vegetated surfaces, and soil surface wetness in bare and sparsely vegetated surfaces. Change in vegetation is reflected in Leaf Area Index (LAI)[22], which was consequently also found to be important (cf. McCarthy, 1996). With sufficient moisture and vegetation[23] conditions energy flow density is effectively decreased by a vertically closed evapotranspiration - condensation cycle (Falkenmark, 1986; Flohn, 1987; Victoria, 1991; Avissar, 1995)[24]. Even small changes in vegetation (i.e. stomata conductance, albedo[25]) can change the energy and water dynamics. This has been demonstrated with plot scale studies (Kedciora *et al.*, 1989; Gay and Bernhofer, 1991; Taniguchi, 1991; Veen *et al.*, 1991), meso scale atmospheric models (Avissar, 1993b), global circulation models (GCM), and nested models of the two latter scales (Skelly *et al.*, 1993). Model results are however, contradictory. Shukla and Mintz (1982) and Shukla *et al* (1990), using GCM, found that tropical deforestation reduced precipitation, whereas Avissar (1993b and 1995), using a meso scale model, and Henderson-Sellers and Gornitz, (1984), using a GCM, demonstrated increased precipitation by convective precipitation following patchy vegetation clearance. The results of the plot studies are more uniform with densely vegetated patches being able to attract water and energy fluxes from adjacent sites with less vegetation.

Plot studies also reveal that disturbance, registered as fluctuations in light, temperature and wetness, increases with gap size (Canham and Marks, 1985; Ghuman and Lal, 1987). Accompanied by nutrient mobilisation via increases in organic breakdown and weathering (Reddy and Patrick, 1975; Lund and Goksoyr, 1980; Orchard and Cook, 1983)[26]. It is also widely recognised that clear-cutting leads to a reversal of ecological development, including a simpler (and more direct) relationship between rainfall and runoff, with larger flood peaks and raised groundwater table in the discharge area as well as nutrient mobilisation (Kihlberg, 1958; Bosch and Hewlett, 1982; Grip, 1982; Rosén, 1984; Simonsson, 1987; Federov and Marunich, 1989). In many cases this problem is “managed” by even further short circuiting the water cycle through drainage (Simonsson, 1987; Sirin *et al*., 1989).

The model results and observations disagree on magnitudes, and even directions of change, which can be taken as a corroboration for the hypothesis of system non-linearity over different scales; which leads to the next topic - hierarchies and communication.

A hierarchical organisation of interfaces

Dissipative water processes and reciprocal interfaces (i.e. life) are organised as a nested hierarchy[27] (Allen and Starr, 1982; O’Neill *et al*., 1986). The processes of life are dependent on boundaries[28], which envelop different functions[29]. 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), suggested for instance by Holling (1992)[30] of the continuos hierarchy include tree stand, patch and catchment (Fig. 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[31]. The quanta communicate via different (waterborne) signals up and down the scales[32]. 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 due to asymmetries (overconnection)[33] or lack of interfaces (underconnection)[34]. System efficiency and integrity is dependent on reciprocity in communication, and closely connected to vegetation and accumulated capital of organic matter in the forest floor (e.g. Bormann and Likens, 1979; Gorham *et al*., 1979; Vitousek, 1985; Holling, 1992). Unprocessed signal streams at one scale will escape as noise, perturbating other scales. The most important components of the landscape system are patches[35] of different vegetation and their dynamic boundaries (synonyms: transition zones, ecotones)[36] (e.g. Wiens, *et al*.; 1985; Pringle *et al*., 1988; Naiman and Decamps, 1990; Holland *et al*., 1991; Hansen and di Castri, 1992). The ecotone is very different if one regards a single patch or a catchment. Observation scale decides both the length and the size of boundaries (Mandelbrot, 1982). It is emphasised that any formation of discrete (study) units is just epistemological[37], and can have no ontological[38] prevalence.

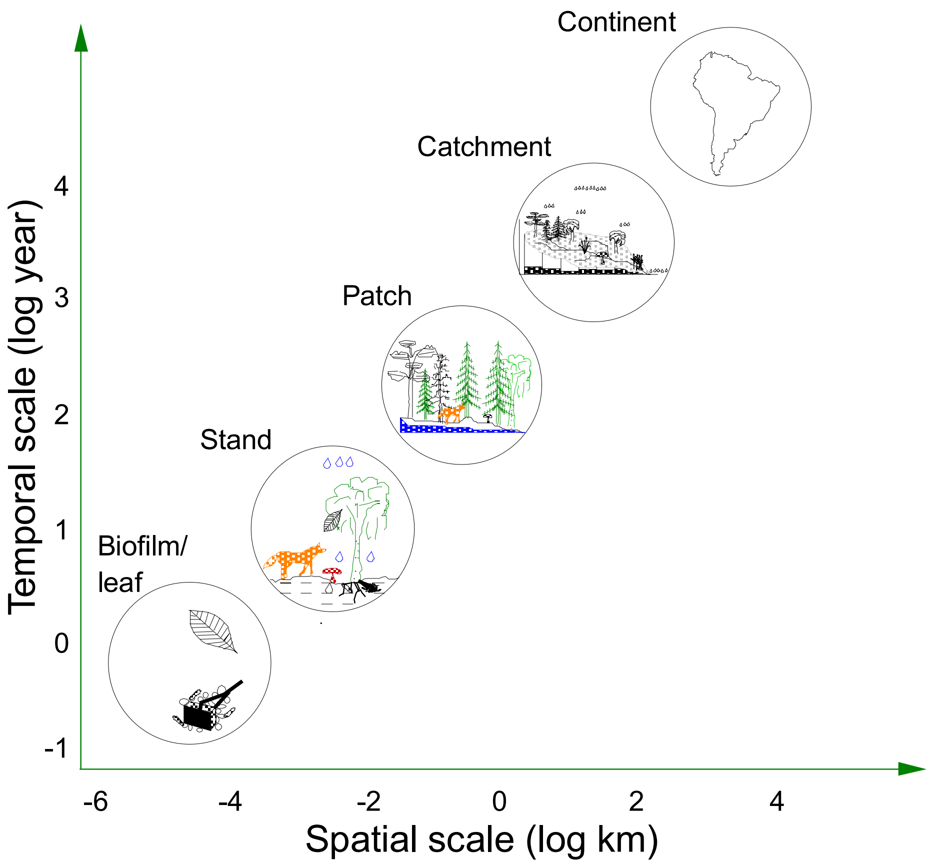

Fig. 1 Hierarchical organisation of natural frequencies and quanta of energy dissipation (from Gumbricht et al., 1996a).

Integrated water studies and concepts

Following the hydrologists reformulating and surveying the origin of stream water (e.g. by the use of tracers as chemical fingerprints - see above), limnologists and ecologists emphasised that the river and its valley form an integrated whole (Hynes, 1975). Together with amongst other things the well known relation between soil profile development and water transport (from soil science) this led to improved understanding and more holistic perspectives of biogeochemical processes in both the hill-slope and the flood-plain.

Emanating from work done by Tóth (1963) and Gustafsson (1968), runoff, water quality and vegetation patterns have been successfully dissected by dividing the landscape (at different scales - or fractals) into recharge and discharge areas (see above). In general the recharge area decreases under wet conditions, and functions as a net exporter (source), with the dichotomously changing discharge area being a net accumulator or sink (e.g. Richardson *et al.*, 1992; Norrström, 1995). The accumulating discharge zone harbours wetlands and riparian forests in lower slope positions with unique regulatory properties; their influence on evapotranspiration and nutrient capture largely exceeds the extent of their areas. Due to high turnover rates, this ecotone has a high efficiency, and is well suited as a boundary for preventing fluxes of water, particulate matter and dissolved nutrients and matter from leaving the hill-slope and entering the stream (e.g. Lowrance *et al*., 1984; Peterjohn and Correl, 1984; Howard-Williams, 1985; Jacobs and Gilliam, 1985; Pinay and Decamps, 1988; Smith, 1989 and 1992; Lowrance, 1992; Hillbricht-Ilkowska, 1995). This has led to a wide-spread application of wetlands and riparian zones for water quality management (see Gumbricht, 1992b; 1993a and b). Later research strongly indicates that wetlands and riparian forests are better depicted as transformers of nutrients rather than sinks (e.g. Nichols, 1983; Brinson *et al*., 1984; Hemond and Benoit, 1988; Brix and Schierup, 1989; Hillbricht-Ilkowska, 1995), with transformations tightly coupled to water flow, organic matter turnover, redox distribution and other matter cycles, including e.g. iron, aluminium and clay (Reddy and Patrick, 1975; Boström *et al*., 1982; Gumbricht, 1993a and 1996b).

In the flood-plain, combining the ideas of site bound biogeochemical cycles and unidirectional water transport led to the nutrient spiralling concept (e.g. Newbold *et al*., 1981; Pinay *et al*., 1990). Another merging hypothesis that developed was the river continuum concept (RCC), which treats the river profile as a continuum of physical gradients and associated biological adjustments (e.g. Vannote *et al*., 1980; Minshall *et al*., 1985). According to these concepts, the importance of water as a unidirectional flow vector constitutes in itself a tendency towards both homogenisation (material mixing) and self-sustained spatio-temporal heterogenisation. A more recent conclusion is that these two contrasting tendencies create dynamically shifting mosaics of vegetation patches (e.g. Naiman *et al*., 1988; Pringle *et al*., 1988; Pinay *et al*., 1990); an analogue to the shifting mosaic steady state concept in forest ecology (e.g. Bormann and Likens, 1979; White, 1979). The ecological stability of the mosaic (in both schools) is regarded as an important factor for nutrient turnover and redistribution within the catchment, and the mosaic of both the hill-slope and the river are used to explain dynamic functions (Hillbricht-Ilkowska, 1993). This theory is now adopted in landscape management strategies (e.g. Forman, 1989; Holland *et al*., 1991; Fox *et al*., 1995).

The pivotal role of water in connecting biogeochemical cycles and sustaining life processes has only been more recently acknowledged (Eagleson, 1986; Stumm, 1986). Integrated studies emphasising this are notably the suggestions of Falkenmark (1986 and 1991) and Ripl (1995). Falkenmark (e.g. 1986 and 1991) divides water into a short structuring cycle, and a long eroding cycle, with distribution between the two being highly dependent on land cover and climate. She also emphasises the role of man as forcing agent, and the reciprocal role of water for both man and nature (Falkenmark and Suprapto, 1992). These ideas have had widespread influence as initiators of other holistic studies and approaches (see Proceedings from the Stockholm Water Symposium 1992-1996)[39].

The increased understanding of the links between the catchment landscape and the river aroused calls for holistic approaches in water resources management (e.g. Karr and Schloesser, 1978; Falkenmark, 1986; Castensson *et al.*, 1990). Subsequently this led to river basin founded approaches for water management in many countries, including France (Gustafsson, 1989), Germany (Gumbricht, 1991) and Sweden (Gustafsson, 1992). Since the publication of the Brundtland report (WCED, 1987) there is a surge in concepts and tools originating in this understanding and emphasising sustainable development (e.g. Wiman, 1992; Svedin and Hägerhäll, 1992; Merret, 1995; Gustafsson, 1996).

Modelling water transport and erosion

In a complex world, a model is a powerful tool for distilling the phenomenon under study down to its essential features. Traditional modelling of earth surface processes has relied on mass-balances and linear cause-effect relationships (see Papers IV and V). Prediction of runoff, nutrient fluxes and erosion have been done by empirical coefficients of losses[40;41] and area characteristics of varying land coverage. This has provided accurate predictions of scale averaged[42] turnover of water and other biogeochemical cycles under steady state conditions. The empirical evidence for large (up to 2 to 3 orders of magnitude) increases in runoff, nutrient losses and erosion following vegetation clearance, agricultural intensification and urbanisation is overwhelming (for reviews see e.g. Bormann and Likens, 1979; Bosch and Hewlett, 1992; Beaulac and Reckhow, 1982; Rekolainen, 1989; Baker, 1992). However, scale effects and system order (i.e. along flow paths), among other effects, undermine the use of such coefficients (e.g. Kundzewicz *et al.*, 1991; Dyck and Baumert, 1991; Heathwaite and Burt, 1991). To be able to predict coherence in changes in (forcing) functions, structures and process couplings there is a tendency towards more physically based modelling.

Physical models based on continuum assumptions, and the laws of mass and energy conservation have led to mathematical-physical descriptions of water processes (e.g. Freeze, 1970a and b), and coupled weathering and erosion processes (e.g. USDA, 1995). Simplifications have been introduced for building distributed 3-dimensional (3-D)[43] field models of for example hydrology (e.g. SHE - Abbot *et al.*, 1986), and erosion (e.g. CREAMS - Kniessl, 1980). Stemming from the *variable source area concept* Bernier (1982 - quoted in Troendle, 1985) and Troendle (1985) developed a 2-D physical hydrological model using increments in flow strips. In a simplified version of the original model, TOPMODEL (Beven and Kirkby, 1979; Quinn *et al.*, 1991), empirically derived topography and soil characteristics govern water content and extension of the saturated zone.

As large catchments tend to average small scale phenomena, traditional concept-lumped models, based on either physical parametisation of the unit hydrograph (e.g. Maidment, 1993a) or lumped soil moisture accounting and routing (as e.g. the Sacramento model - Burnash *et al*., 1973, or the Swedish HBV model - Bergström, 1976 and 1992), perform as well as the more elaborate models. This has fostered an intermediate approach, dividing the drainage basin into hydrological response units (HRU) - regions where important processes are regarded as less variable (e.g. Knudsen *et al*., 1986; Kite and Kouwen, 1992; Flügel, 1996).

The success of the finer separation of catchments for more physical correct representations of processes is increasingly questioned (e.g. Klemeš, 1986; Beven, 1989; Grayson *et al*., 1992b; Moore *et al*., 1993). Only if data with adequate spatial and temporal resolution are at hand the applications of sophisticated, multi-layered, physically based models are applicable (Ostrovski, 1991)[44]. Moreover, the present state of the art models fail to adequately portray the catchment hydrological system (e.g. Gan and Burgess, 1990a and b; Grayson *et al*., 1992a and b). It has been shown several times that hydrological models are over-parametised, and that three to four parameters in general are enough to fit model output with a measured hydrograph (Mein and Brown, 1978; Kachroo, 1988; Klemeš, 1988).

To summarise the discussion, a holistic portrayal of system processes must consider component order and juxtaposition, as well as scale. Due to emergent qualities, averaging of behaviour in complex systems is meaningless, and needs to be substituted with a phase related analysis recognising the scale of observation. The need is becoming urgent since meso scale models of ecology and hydrology are increasingly coupled to the larger scale global circulation models (GCM). This has stimulated calls for global approaches to hydrology and for closer links between hydrology and related subjects of geology, meteorology and ecology (Eagleson, 1986; Klemeš; 1988 Shuttleworth, 1988). A recent development is nesting different scales by, for instance letting the GCM parametise the forcing functions of smaller scale models of ecosystem (Schimel and Burke, 1993), vegetation and hydrology (Nemani *et al*., 1993). Smaller scale models can in turn be used for parametising sub grid processes in the GCM (Lee *et al*., 1993; Moore *et al*., 1993; Avissar, 1993a and b). This model nesting is often built on GIS and remote sensing.

Modelling the landscape with GIS

Identification and classification of landscape morphology and topology are pre-requisites for many environmental studies, with GIS and remote sensing progressively applied as integrated tools (Argialas and Harlow, 1990; Goodchild *et al*., 1993). Traditional image interpretation and object classification are based on pixel-wise statistical signal recognition in continuous field data signals (i.e. different wavebands) (for reviews see e.g. Richards, 1993; Lillesand and Kiefer, 1994). Present status in image interpretation methods are object oriented methods, considering relations between for example waveband reflections and ancillary GIS data and spatial relations, with knowledge inferred via an expert system (Fig. 2). 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. Recent development has been towards compact transparent rules and fuzzy membership functions (e.g. Leung and Leung, 1993; Dymond and Luckman, 1994). Another development has been to use neural networks for inductive rule structuring based on training data sets (e.g. Civco, 1993).

Increased data availability and the ease with which distributed data layers are created from point and line data, and remote sensing (Bork and Rodhenburg, 1986; Ottle *et al.*, 1989; Pilesjö, 1992), have led to a wide spread coupling of GIS and remote sensing to existing (non-topological) cause-effect models in for example hydrology and erosion studies (e.g. Kovar and Nachtnebel, 1993 and 1996). In hydrology notably the variable source area concept has been widely adopted to GIS by the use of digital terrain models, and the algorithms for antecedent soil moisture conditions suggested by Beven and Kirkby (1979) and O´Loughlin (1981, 1986)[45]. In erosion modelling the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) and its corollaries (e.g. Renard *et al.*, 1991; Glanz, 1994) have been widely adopted to GIS (e.g. Sivertun *et al.*, 1988; Pilesjö, 1992; Wilson, 1996). More physical hydrological and erosional models, including the unit hydrograph (Maidment, 1993a), lumped models like HBV (Lindström *et al.*, 1996), and semi-distributed HRU models (Flügel, 1996), are increasingly using GIS and remote sensing for parametisation (see Maidment, 1993b). The most elaborated and widely distributed models like the hydrological SHE model (Abbot *et al.*, 1986) or the LISEM erosion model (de Roo *et al.*, 1996) incorporate a GIS in themselves.

However, investigations in different parts of the catchment have shown that the variation in physical and chemical properties vary also on a small scale (e.g. Espeby, 1989; Skyllberg, 1993; Norrström, 1995). A river basin reveals more information at higher spatial resolution, apparently without limit (cf. Mandelbrot, 1982). Following for example Beven (1989) it can hence be strongly argued that distributed models are also lumped, on a grid scale. The squeezing of the information in point and line measurements to distributed data sets thus usually makes no sense (cf. Klemeš; 1986). Avissar (1993b, 1995) has thus suggested the use of higher statistical moments for sub-grid parametisation (cf. Moore *et al.*, 1993). Another attempt has been to use ranking of homogenous response units (or base assessment maps) for correlating processes and cumulative impacts (Grossmann, 1991; Grossmann and Eberhardt, 1992). The latter approach is now also leading to full coupling of spatially distributed models to temporal processes (e.g. dynamic maps - Grossmann and Eberhardt, 1991).

Spatial decision making and landscape planning based on overlay maps was popularised by McHarg (1969). Most early applications of GIS in policy and decision making followed this static and simplified approach (e.g. map algebra - Tomlin (1990)). However, many strategic problems (e.g. site and route selection) that are called on for solutions are ill-structured and require several steps before reaching a solution (Fedra, 1993). This has fostered a plethora of techniques now adopted to GIS for improved spatial (and temporal) allocation and management. Expert system(s), multi-criteria evaluation (MCE)[46] and linear programming (LP) are widely applied decision tools for analysing complex trade-offs between multiple criteria and conflicting objectives in GIS (e.g. Carver, 1991; Chuvieco, 1993; Pereira and Duckstein, 1993). Using fuzzy membership functions (as in MCE) emphasises the role of the decision maker in selecting levels of risk and uncertainty (i.e. a soft decision making). There is thus a trend in using GIS for scenario creation acknowledging errors and uncertainties. Graphical user interfaces and visualisation tools are also presently under strong development (e.g. Bishop and Hull, 1991), and recently reported to be coupled to comprehensive water resource management tools (Lin *et al*., 1996).

PROBLEM

With urban expansion and agricultural intensification natural systems with maximised gross productivity are replaced by systems with maximised net productivity. The tight conglomerate of processes and matter flows is loosened, with subsequent increased outflow losses. System efficiency and integrity is further deteriorated by rupturing of the in-stream ecosystem at different scales (Vorosmarty *et al*., 1986; Thorne, 1991; Golladay *et al*., 1992; Montgomery, 1996), and by straightening and channelling (i.e. homogenisation) of the stream itself (Pinay *et al*., 1990). The leaking system enters a transient state of erosion, large scale eutrophication, acidification, and change of climate. These processes have become globally cumulative (Turner *et al*., 1990, Brouwer *et al*., 1991), linking global change to regional flip-flop behaviour and local surprises (cf. Holling, 1986), such as illustrated by floods in Central and Western Europe (1994), Sweden and Norway (1995), and at the time of writing in China (1996)[47]. The present development is unsustainable. A new water integrated land use planning strategy for sustainability in the spirit of the Brundtland commission (WCED, 1987) and Agenda 21 is therefore needed.

The obvious spatial dimension of the problems calls for the use of GIS. At present GIS is mostly loosely coupled to traditional models for creating distributed data sets, and for display of these data sets and model output (Kovar and Nachtnebel, 1993 and 1996). To take advantage of the topological and site specific relations represented in GIS, a tighter model coupling is needed both for mapping and modelling. Present models often fail to explain system key relations, and are usually applicable only for narrow ranges in scales and forcing functions. There is an urgent need for robust models able to predict system behaviour in a transient world. Many studies now recognise this, and seek solutions either in nesting reductionist models of different scales, or try to use holistic approaches based on basic laws of biology, chemistry and physics, and heuristic[48] pattern recognition. The thesis acknowledges the latter approach, but elements of the former are introduced in the last study (paper VI).

The thesis specifically deals with the problems of (**i**) formulating a system concept applicable for understanding (consequences of) transient processes and changes; (**ii**) representation of relations between non-random spatial processes and objects; and, (**iii**) modelling the reciprocity between dynamic processes and spatial patterns.

OBJECTIVES

The main objective of the study has been to develop a concept and a set of tools that could be used for holistic and integrated landscape management, recognising water as the organising agent. In practical terms this led to a sequentially dependent development of operational tasks:

- definition of a synthesising concept for sustainability based on natural science,
- development of a rule based system for knowledge based classification of multisource spatial data where deductive knowledge of process-pattern relations could easily be inferred (notably applicable for improving land surface object classification from combined satellite images and ancillary GIS-data),
- development of a hydrological system model emphasising the defined concept, and closely coupled to distributed data sets with topological representations (i.e. GIS).

It was emphasised that the tools should be transparent, facilitating hypothesis testing, and should be easy to use in higher education, and by for example planners and managers. As only few models were adapted to GIS, and none of them based on the defined concept (paper I), much of the study focuses on the integration of different data sources and models. Both the rule based expert system (Papers II, III and V) for landscape pattern classification and the hydrological model (Papers IV, V and VI) are integrated with GIS and remote sensing. It is emphasised that the models aim for accomplishing better understanding of key relationships in landscape patterns and processes; to improve the possibilities for sustainable (re)development. The aim was thus not primarily to develop sophisticated, but rather reductionist models for image classification and rainfall-runoff modelling.

HYPOTHESIS

The main hypothesis proposed is that the land surface is a non-random structure, created by processes in the water cycle, which, through evolution, life has utilised for creating an efficient (long living) system on different scales. Deduction of this hypothesis leads to the operating assumptions of, (**i**) the landscape structure having a process derived pattern logic (which should lead to improved digital land surface classification when declared as knowledge relations); (**ii**) the hydrological cycle being intimately coupled to the vegetation pattern on different scales (which should lead to a reformulation and improvement in models of earth surface processes); and (**iii**) viability and longevity of natural ecosystems (i.e. sustainable development) being dependent on the coherence in spatio-temporal distribution of communicating processes and patterns (which, however, is partly tautological[49]). The derived assumptions should be predisposed to be falsified (sense Popper, 1978).

OUTLINE AND METHODS OF THE INCLUDED STUDIES

The first paper elaborates on the holistic energy-transport-reaction (ETR) concept put forward by Ripl (1995)[50]. The concept is based on thermodynamic premises, and water as the main organising agent of the non-random landscape structure. Paper II describes landscape pattern classification, and a rule based expert system (GUIDE) developed for incorporation of knowledge of the landscape logic in such classifications (Fig. 2). The paper also compares the performance of GUIDE to that of traditional classification. In paper III GUIDE has been applied to Cyprus, where the resulting land cover map and the ancillary data was used for allocating future sites for infrastructure development. The paper also discusses the application of structural indicators for landscape management.

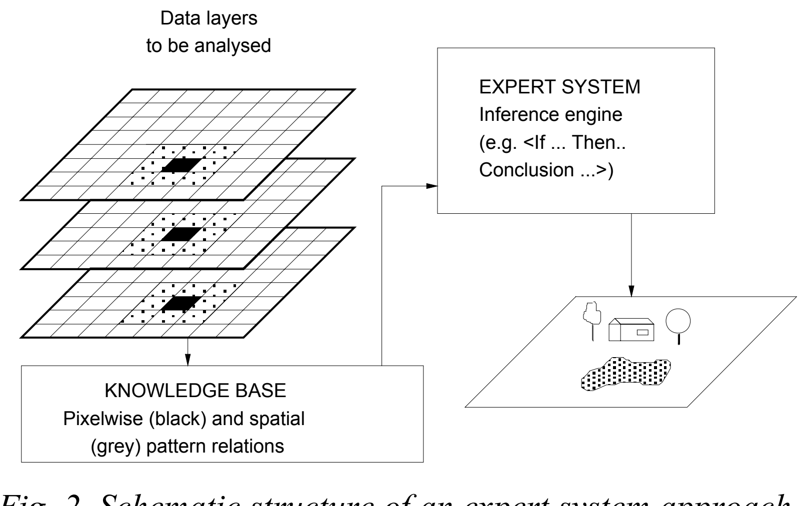

Fig. 2 Schematic structure of an expert system approach for spatial data analysis (from Paper II).

Paper IV presents a hydrological model (PHASE) coupled to GIS and remote sensing that emphasises the Energy-Transport-Reaction concept (i.e. vegetation-water reciprocity). The model is regionally calibrated using a few parameters (see below), with physically based key indicators of vegetation, size and elevation automatically extracted from GIS when applied to a specific catchment (Fig. 3). The underlying assumption is that synoptic indicators for lumped sub-grid parametisation is a more robust approach (i.e. less error sensitive) than distributed modelling. Paper IV includes application of the model in Cyprus and Poland. The two last papers present other applications of the tools. In Paper V, elevation, vegetation cover, runoff and erosion have been modelled for a Himalayan drainage basin using both GUIDE and PHASE. In Paper VI, PHASE has been used for predicting hydrological effects of global warming induced by increases in atmospheric carbon dioxide levels and subsequent vegetation changes.

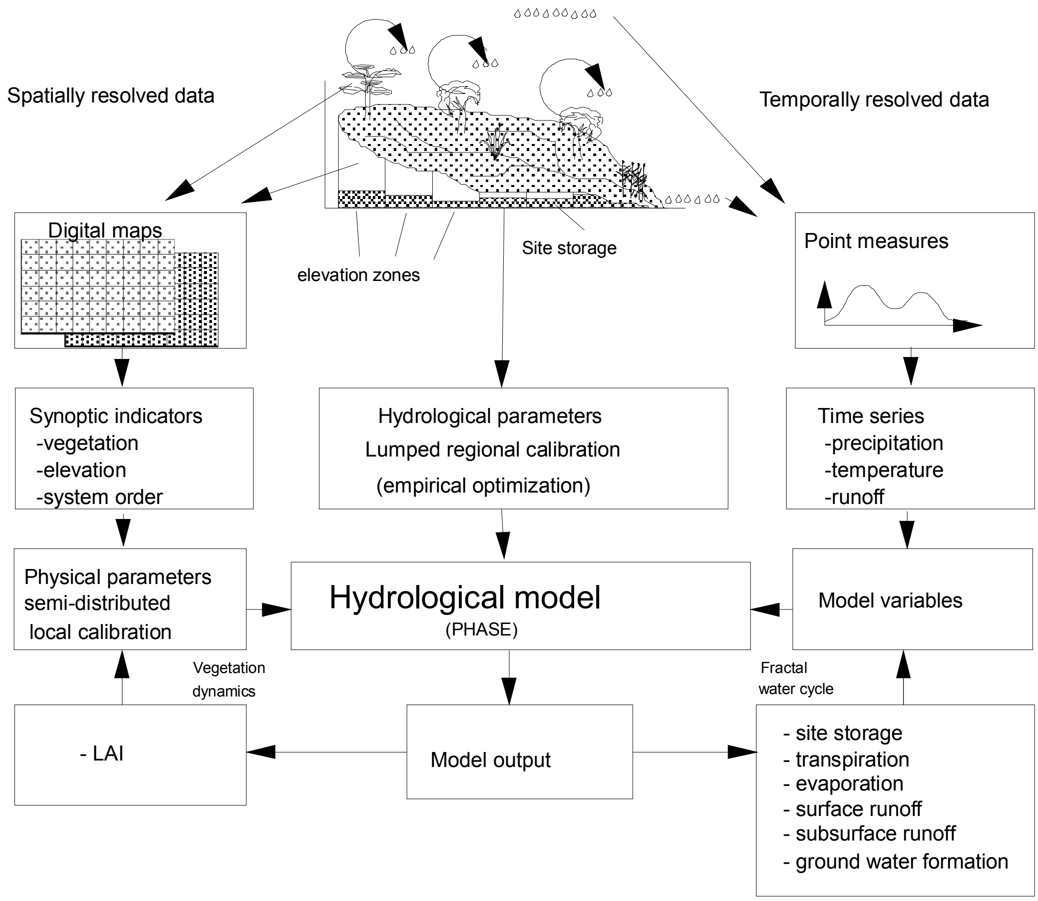

Fig. 3 Schematic relation of landscape spatial structure and hydrological functions as interpreted in PHASE. The model is regionally calibrated by lumped hydrological parameters for soil moisture accounting and routing. Local calibration is based on semi-distributed physical parameters derived from GIS and remote sensing. Dynamic feedback processes can be introduced by a simple vegetation growth and decay function, and by a fractal water cycle (figure modified from Paper III).

The scale of the studies have been the catchment, as this is a recognised natural scale in both hydrology and ecology, and as it has certain advantages in measuring the outgoing signal. The methodological approach is summarised in Fig. 4.

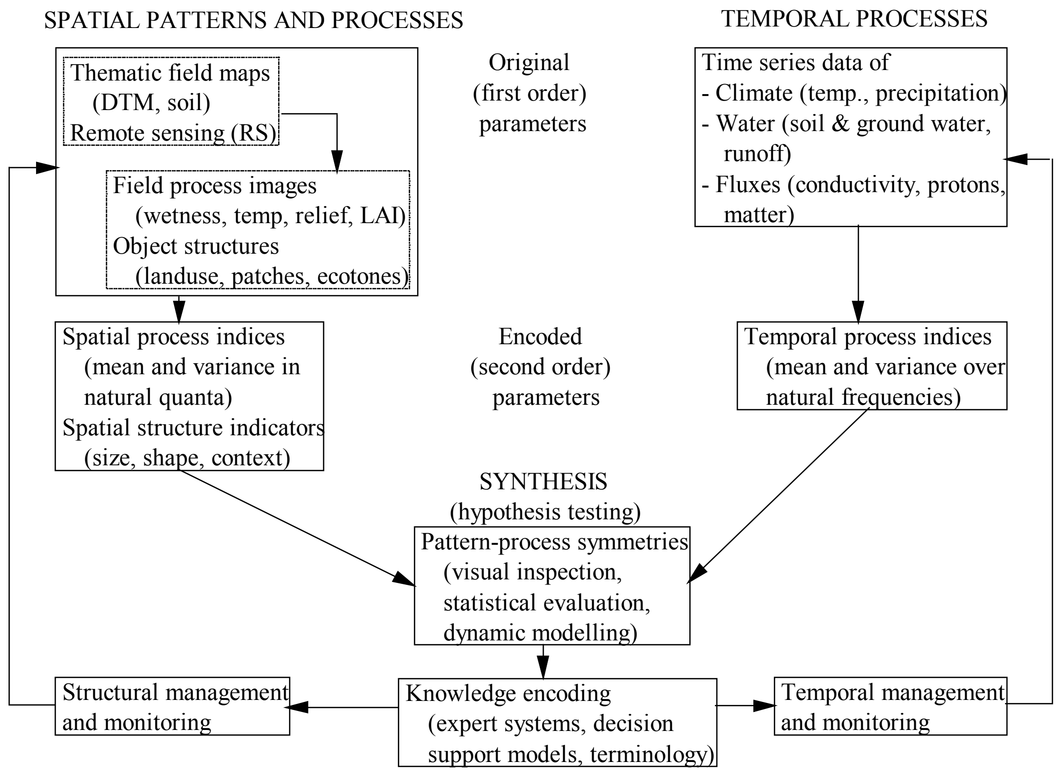

Fig. 4 Summary of methodological approach (modified after Gumbricht, 1995 and Gumbricht et al., 1996a).

STUDY SITES AND DATA SETS

Study sites were selected to represent different climatic, geographic and vegetation regions, but were also partly dictated by access of good data, teaching needs, and different co-operative projects. The study areas thus represent Cyprus, the Himalayas, Poland and Sweden. A short description of the main study sites and data sets used are presented below. For more details see the papers.

Cyprus

The semi-arid Mediterranean island of Cyprus covers an area of 9251 km^2. Annual precipitation varies from 300 mm in the rain shadow of the Troodos mountain, to approximately 1000 mm at its peak. The mountain and its slopes are covered by coniferous forests, with bushy landscapes spreading over the lower parts as a result of over grazing. The plains are dominated by agriculture, with increasing irrigated areas (Cyprus Water Development Department, 1989). Tourism and an expanding population has led to a large development of urban areas and infrastructure. Cyprus was chosen as a study area mainly because of its shifting climate and geography, but also for the very good spatial and temporal data available. Cyprus has a dense network of hydroclimatic measuring stations of high quality (Kypris and Neophyto, 1994), that was used for developing the hydrological model.

The Himalayas

The study in Paper V comprises the Sutlej river basin upstream of the city of Rampur in the state of Himachal Pradesh in North Western India and Tibet in China. The study area is largely in the Tibetan rain shadow; climate is characterised by the absence of monsoon rains. Elevation ranges from 2000 to 7000 meters above sea level. Bedrock is granitic with a varyingly thick soil cover of mainly glaciogenic origin, with the upper part still being glaciated. Lower parts are dominated by coniferous forests. At higher altitudes vegetation is sparse or absent, partly resulting from severe erosion, partly due to overgrazing. The study was undertaken for the planning of a hydropower plant in Sutlej, including a dam in the Baspa tributary.

Poland

The studies in Papers II and partly IV were undertaken for Krutynia and Jorka catchments in the Great Mazurian Lake District, Poland. This area was chosen in a co-operative program between the Royal Institute of Technology (Sweden) and several Polish institutes (Gumbricht and Renman, 1995). The area is in the temperate zone, and was formed by the outskirts of the last glaciation. It is characterised by till and sandy sediments forming a hummocky terrain. Hilltops are dominated by coniferous forests, with an increase in deciduous trees in the discharge areas of the slopes and wetlands at the bottoms. Today grazing dominates much of the hill-slope. Both the rule based system (GUIDE) and the hydrological model (PHASE) were applied to the studied catchments.

Sweden

Two different urban environments in Sweden have been studied. In Uppsala (100 km north of Stockholm) a larger study on urban green patches and hydro-ecological processes is presently going on (Gumbricht *et al.*, 1996a). Uppsala has approximately 120,000 inhabitants. The study reported (in Paper I) is based on comparing high temporal measurements of flow, conductivity and temperature in the storm water pipe system of three districts with different degrees of exploitation (Espeby *et al.*, 1996). For the small town of Olofström (situated in Southern Sweden, approximately 500 km south of Stockholm), images showing urban form, leaf area index, wetness and temperature have been encoded and compared. Olofström was chosen for teaching reasons. Both sites are within the temperate region, glaciated during the last glaciation, and dominated by coniferous forests. Both sites also have a flat topography.

SUMMARY OF THE INCLUDED PAPERS

Landscape processes and structural coherence (mainly Paper I)

In paper I it is suggested that water has three dialectic processor properties: evaporation-condensation, dissolution-crystallisation, photosynthesis-respiration. Life uses these properties for controlling energy dissipation, which is manifested in coherent patterns of temperature, precipitation, runoff and subordinate chemical processes with respect to space and time. The hierarchical organisation of life is emphasised. The smallest autonomous unit being able to control energy dissipation must contain five reciprocal components: autotrophs (plants), a food chain of heterotrophs (animals), destruents (e.g. bacteria and fungi), a detritus pool with nutrient storage, and water. In an aquatic environment the biofilm is such a *coenotic* unit[51], on land a tree and its surrounds (i.e. stand). Sustainable development is defined from the ratio between cyclic processes and losses, which is a way of measuring the internalisation of nutrient cycles, and thus reflects the longevity of the system.

Remotely sensed imagery is used to compare vegetation density and wetness and temperature distributions. Fragmented green patches in urban environments have a cooling effect, and preserves a local water cycle, whereas urban areas and open lands lead to bleeding "hot spots" (cf. Gumbricht *et al*., 1996a).

Discussion

High gross productivity accompanied by abundant vegetation and thick humus layers increase the water storage capacity and the active water pool. The vertical water cycle becomes more closed leading to a hydromorphic and stable landscape (Monteny and Casenave, 1989; Victoria *et al*., 1991; Avissar, 1995; Paper IV). In unvegetated and/or disturbed areas, water processes are spontaneous, with a lower degree of local process closure. Such landscapes are characterised by lower efficiency, a tendency further accelerated by randomised energy input (particular in urban regions). Solar energy pulses will not be dampened by biological control, but translated into oscillations of temperature and moisture variations, triggering a lower efficiency and higher loss rates. Preferential outflow of salts and nutrients leads to regional eutrophication of receiving waters, and a depleted soil with falling pH. The understanding of landscape process-pattern symmetries derived from the Energy-Transport-Reaction concept and the included study, elicited calls for better models describing spatial and temporal patterns and process coherence.

Image classification, structural encoding and spatial allocation (Papers II, III and V)

Both the natural and anthropogenic landscapes have process derived logics, for which domain experts have developed corresponding semantics. Inferring such knowledge in image classification could potentially lead to improved classification results, as well as new types of “risk”, “potential” and “need for action” maps. Papers II and III describe a forward driven rule based expert system incorporating fuzzy logic for classification of combined remotely sensed imagery and ancillary GIS information (e.g. elevation, geology, soil). The system is based on pixel-wise classification (cf. Fig. 2, p 14) using declarative syntax in the form “if condition 1 ... (and condition 2 ... and ...) then conclusion ...“. Rule structuring can be either manual (declarative) or automatic (procedural), with the system intended for automatic signature extraction (based on training data) for quantitative field data (e.g. satellite imagery), and manual updating with qualitative relations to both field (e.g. elevation bound land use) and object data (e.g. soil bound vegetation). The rule based program (GUIDE) was used to create different maps for all study sites except Olofström in Sweden. A second part for contextual post-classification is in its initial phase of development (Gumbricht, 1995), and was used for the Cyprus study only (Paper III).

Input data for the classification in Poland (Paper II) included two Landsat TM scenes (from April and June 1990, respectively). Catchment and stream network delineation, and elevation and soil classes were manually digitised from maps in a scale 1:50,000. Pre-processing of the TM scenes included positional transformation, data compression using principal component analysis (PCA) and calculation of Leaf Area Index (LAI), and wetness index (as given in McCarthy, 1996). Calculated LAI difference (June minus April) was taken as an indirect measure of vegetation growth. Using training data for 8 output classes, signature profiles for all the remotely sensed data were automatically extracted. The signatures were then manually updated based on knowledge of physically interpretable field relations, i.e. wetlands and contributing (“updrain”) areas, land cover and vegetation growth. The result was compared to traditional maximum likelihood classification, that used the same training data and was also manually updated. Classification accuracies were similar for both methods (a Kappa index[52] of 75 % correct for GUIDE, 71 % for maximum likelihood). However, manual updating did not improve the classification, and manual inspection of positional accuracies revealed larger errors (two to three pixels) than suggested by the transformation formula accuracy (less than one pixel). This, together with poor quality in the ancillary data, discredited the use of knowledge relations between the different data layers.

The classification of Cyprus used one Landsat TM scene (obtained August 1984), one Landsat MSS scene (obtained April 1987), and ancillary data on elevation, geology and soil (described in detail in Gumbricht *et al.*, 1995). Maximum likelihood classification of Cyprus (using the Landsat TM scenes) gave a Kappa index of 25 %. Manually inferred knowledge rules performed better than automatic. Highest Kappa index was 64 %, with 12 % of the cells remaining unclassified. It was hypothesised that the latter were composed of either mixed categories or unique transition zones (i.e. ecotones). Thus they were categorised based on spatial information from their a priori classified neighbours, inferred via expert rules. Accuracy of the final land cover image was 67 %.

In paper III, GIS was used as a decision support system for allocation of future infrastructure on Cyprus. Multi Criteria Evaluation (MCE) was used in a compromise solution, seeking to secure land needed for agriculture, tourism, industry and urban expansion in the next decade. MCE was also compared with GUIDE for identifying suitable areas for reforestation[53].

Encoding of spatial object data into structural indicators was done for forest patches in Papers I and III. In paper I it is shown that the size of the forest patch influences temperature and wetness stability, whereas patch form seem less important. However, core areas have lower temperature and higher wetness, and thus form should have some influence. In the Cyprus study (paper III) number of patches and edge (i.e. ecotone) length were used as an indicator for describing structural landscape changes following a GIS derived reforestation scenario.

In the Himalayan study (Paper V) remotely sensed data and GIS were combined for creating digital data sets of elevation and vegetation. A small tributary (at elevations 2000-5000 meters above sea level) with high resolution satellite (SPOT) derived data was used for extrapolating data to the whole Sutlej drainage basin. Model errors were quantified by comparing the created data set with the original small data set in the overlapping region. The estimated errors were inferred in erroneous models over elevation and vegetation. Using field data on total erosion GUIDE was used to map erosion risk, acknowledging the errors by using a fuzzy approach. The erosion model was also updated with logical relations, supported by empirical studies (see Lindholm and Åkre, 1996). Model validation showed poor relations to the field data; positional accuracy being a major problem since a single pixel mismatch easily distorts field verifications in qualitative data.

Discussion

The power of the rule based expert system lies in its being transparent, and comparatively easy to use for different applications. It has been successfully implemented in higher education (Gumbricht, 1996a; Gumbricht and McCarthy, 1996) for e.g. image classification and mapping of source areas of non point source pollution. The inclusion of fuzzy logic, and assignment of membership of a single data point to all spatial output classes facilitates post-processing and updating, such as when used in image classification. Forward rule structuring for site identification requires domain expert knowledge, and is more difficult than the application of goal seeking methods like MCE. However, the forward driven rule output is more transparent, and can easily be used for updating and hypothesis testing. Compared to traditional Boolean logic of map overlay or statistical classification, adoption of fuzzy methodologies and expert systems provide a more satisfactory methodology for land evaluation. Good positional accuracy is crucial when combining different data sources through manually inferred knowledge relations.

Dynamic modelling of environmental processes (Papers IV, V and VI)

The hydrological model, PHASE, is described in paper IV[54], and is also used for predicting the water cycle in papers V and VI. It is a semi-distributed bucket model incorporating reciprocal and dynamic effects of vegetation and surface topology. Vegetation determines transpiration and a fractal water cycle[55], high gross productivity, large biomass and humic matter leads to a large water pool controlled by vegetation (i.e. a "sponge" effect). Regional calibration is done by optimisation of 3 to 7 parameters (table I), and local adjustment is automatically done by extraction of physical measures derived from GIS and remote sensing. A set of global constants are used for linking vegetation and hydroclimatic reciprocity. The constants were allowed to change under the scenario of increases in atmospheric temperature and carbon dioxide levels with hypothesised subsequent changes in ecosystem metabolism (Paper VI).

TABLE I Definition of constants and parameters in PHASE

Global constants	Evaporation	Defined by temp (alt. potential evaporation), total site storage and *ETTRES*
	Transpiration	Defined by LAI, temp (alt. potential transpiration), total site storage and *ETTRES*
	Veg growth and decay	Defined by LAI, temp and transpiration
	Interception storage	Defined by LAI
Regional parameters	*SITEMAX* (obligatory)	Maximum passive (soil water) storage
(lumped & empirical,	*FIELDC* (obligatory)	Lower threshold for subsurface flow ("field
optimised by fitting		capacity")
of modelled and	*XSUB* (obligatory)	Fraction of subsurface flow to runoff
measured flow in	*XGRW* (0=inactive)	Fraction of subsurface flow to groundwater
calibration periods)	*ETTRES* (0=inactive)	Lower threshold for soil water content ("wilting point")
	FRACPREC (0=inactive)	Fraction of transpired water returning as prec
	TEMPALT (1 = default)	Temp change per 100 m elevation
Local parameters	Area	Total area of elevation zones
(physical, derived	Leaf Area Index (LAI)	Estimated LAI in elevation zones
from GIS and RS)	Flow length[56]	Mean and standard deviation in flow length in elevation zones
	Flow route[55]	Mean and standard deviation in LAI along flow lengths in elevation zones

In paper IV the model was applied to three catchments in Cyprus (chosen to have distinctively different characteristics) and two Polish catchments. For Cyprus, regional parameters were individually optimised using three to four years of daily data. Model performance was then independently tested by using one year of data for the same drainage basin, and transferring of the parameter setting to the other basins[57]. The lumped HBV model (Bergström, 1992) was used in a similar fashion as comparison. Model performance was tested by using the adjusted R^2 suggested by Nash and Sutcliff (1970), accumulated difference and visual inspections of measured and calculated flows. PHASE and HBV performed equally well during the calibration periods (adjusted R^2 varied between 0.5 and 0.7[58], which is acceptable for ephemeral rivers). In the validation period PHASE outperformed HBV. When transferring the parameter setting PHASE performed almost equally well as with individual setting (adjusted R^2 varied between 0.29 and 0.69), whereas HBV failed to portray the flow (adjusted R^2 varied between -1.52 to 0.29). The problem with HBV being that it can be calibrated with a high variance in single parameters (i.e. an example of the problem of over-parametisation), with a subsequent lack of physical relevance (Seibert, 1996).

Data for the two Polish rivers were not of the same quality, and runoff data was only collected on a monthly basis and for one year. Thus one river was used for calibration and the other for validation. PHASE (in an early version) performed better in calibration (R^2 of 0.68 as compared to 0.64), whereas HBV achieved a better result in the validation catchment (0.50 compared to 0.44) (summarised in Paper IV, and elaborated in Gumbricht, 1995).

In Paper V the elevation and vegetation models created over Sutlej in the Himalayas (see above) were used for running PHASE against measured flow in seven sections. Problems with "representativity" of the precipitation data were detected early, and led to the development of a distributed (i.e. GIS based) precipitation model. For each section the drainage area was digitised, and average daily precipitation calculated from elevation adjusted and weighted interpolations. Optimisation for each section was done individually. Model performance (expressed as adjusted R^2-see above) varied between 0.12 and 0.69, with higher values for larger catchments (i.e. the main river). Using erroneous models of vegetation and elevation (see above) performance decreased slightly. For the section farthest downstream (Rampur) the erroneous elevation model was used for creating a precipitation series as well, which led to a slight further decrease in model performance (R^2= 0.56). A major problem was caused by poor temperature data; the three measurement stations are all located below 3000 meters above sea level. Extrapolation to higher altitudes probably gave large errors, and caused problems with snow melt and ablation. Thus the general runoff pattern could be accurately predicted, but with large differences in volumes. The need for better hydroclimatic data covering the region is urgent.

Paper VI examines the effects of climate change on the water cycle over Cyprus, using an unsettled river basin on the Northern slopes of Troodos (the basin was however severely bombed during the war in 1974). Using PHASE, three different scenarios were examined and compared with the present situation by using a five year time series (1989-1994) of daily hydroclimatic observations. The additive scenarios include, (**i**) a temperature increase by three degrees Celsius; (**ii**) CO_2 fertilisation by vegetation growth; and, (**iii**) changes in C:N ratios of dead and living matter with subsequent decreases in decay rates (for elaboration on climate feedback mechanisms see e.g. Dickinson, 1986; Lashof, 1989; Houghton *et al.*, 1990; Gumbricht, 1992c). In all scenarios there is an increased evapotranspiration leading to higher precipitation (through the fractal water cycle). Soil moisture is decreased, as is runoff. However, the model results indicate that the effects of temperature and $p\mathrm{CO}_2$ changes on vegetation and the hydrological cycle are largely unpredictable. Different feedback mechanism give different directions of change.

Discussion

Present cause-effect models of the water cycle largely neglect the interactive role played by vegetation and its distribution. Existing models are thus applicable to narrow ranges of physical conditions, with elaborate models being in addition to this also very data hungry. GIS is thus increasingly used for creating the necessary data sets, with a large risk of seducing the user into a false feeling of data quality and accuracy (Grayson *et al.*, 1993). Despite its simplicity, the PHASE model has performed comparatively well. Together with "transferability" of optimised parameter settings within regions this indicates that the physical parameters vegetation and relief (rather than the soil) are key structures relating to the hydrological response of a catchment.

FINAL DISCUSSION

At a landscape scale water is the major formative agent, with pathways and processes inextricably linked to patterns of relief, vegetation, geology and geomorphology. In the thesis it has been suggested that water has an even more pivotal role than hitherto revealed: as a key element in environmental regulation as an energy absorber, as a unique solvent, and as a raw material in the photosynthesis. In the sustainable landscape these water processes interact in closed cycles in terms of water and matter within hierarchical quanta. When present, vegetation and its products control the cycles. Societal development has cleared the vegetation and opened up the cycles - by which the landscape heats up/cools down, bleeds water (signals are droughts and floods) and matter (signals are eutrophication and land fertility degradation). This suggests that water is the main information carrier with multiple feedback mechanisms for homeostatic[59] regulation of the environment.

Present environmental modelling and management, however are still pervaded by the paradigm (sense Kuhn, 1962) of a simplified small number system (e.g. planetary system)[60]. Applied to arbitrary discretised scales models can be formulated as elaborate mathematical relations. Errors and uncertainties are introduced as stochastic relations, leaving aside the self-organised complexity of dissipative structures. These cause-effect views pertaining to static equilibrium theories, must be substituted for holistic perspectives of the landscape as a continuous hierarchy of reciprocally communicating processes with subordinated pattern logic.

The developed rule based knowledge program (GUIDE) is a useful tool for testing the pattern logic of the landscape. Using domain specific knowledge in landscape classification is straight forward. Compared to traditional classification qualitative relations can be declared. GUIDE can also be used as a tool for inferring management strategies, in which case the resulting spatial allocation can be traced back to the knowledge rules. Together with the fuzzy membership functions assigned to each location, this emphasises the role of the domain expert/decision maker in selecting strategies.

Environmental modelling need to take a step back; models must be kept transparently simple, and "must work well for the right reason" (Klemeš, 1986). The obvious spatial dependence calls for the integration of dynamic models with spatial data sets (i.e. GIS). However, GIS applications are still much an offshoot of earlier non-spatial model approaches. Simple map-algebra is used to generate distributed and error prone data sets. In this study GIS was instead used for generating sub-grid parametisation (in PHASE), under the assumption that this approach is more robust. Models logically consistent with primary natural laws, and based on heuristic pattern recognition can lead to improved management of spatial architectures and coherent dynamic processes.

From the literature survey and the results of the thesis suggested key elements for landscape restitution include cap (or hilltop) forestation for groundwater control and clean water production (cf. Gustafsson, 1986), wetland redevelopment and riparian forestry for hydrographic control and for control of matter losses, and ecological engineering systems for recycling matter (notably nutrients). In urban environments communicating green lungs and highly productive moist areas for recycling of wastewater (wetlands and greenhouses), must be intensively managed to balance the high concentrations of randomised energy and matter.

The tools developed in the thesis show that simple and transparent models based on synoptic key relations can perform as well as traditional alternatives. However, the models are still in their infancy, and the applications should rather be seen as performing initial hypothesis testing. Both GUIDE and PHASE are based on very simple user interfaces, but have nevertheless proven to be effective tools for learning complex process-pattern relations in higher education. A major problem with the rule based expert system GUIDE has been the positional accuracy of the different data sources. Just a simple mismatch of a single pixel distorts the inference of logical rules. It is also clear that contextual relations are very important in landscape pattern classification, and thus a contextual part of GUIDE is under development (the Cyprus study).

Positional errors also cause problems for PHASE, as the intention is to use vegetation (as interpreted in satellite images) distribution along relief (as given by a digital elevation model) as a key indicator. A related problem is the number of algorithms available for estimating vegetation cover and updrain areas in GIS. Initial tests revealed that different algorithms gave very different results and were very sensitive to errors in the digital elevation model (Szczepanek, 1995; McCarthy, 1996). There is thus as yet no automatic inclusion of system order or updrain conditions in PHASE, it being still simply based on elevation zones, and average vegetation cover within those. Another simplification is that the model assumes lumped values for passive water storage capacity, and complete infiltration until saturation occurs[61]. The lack of inclusion of selectively distributed processes like fires or vegetation harvesting is a further drawback. Current developments encounter those problems, and should lead to improved model results.

CONCLUSION

Neither the hypothesis of a process derived land cover pattern, nor the hypothesis of a close coupling between vegetation and the water cycle, were falsified when applied to data of good accuracy. Thereby corroborating the main hypotheses of water being the organiser of land surface patterns and processes. The support for those hypotheses made it feasible to use the models (GUIDE and PHASE) in the scenario applications of erosion modelling, and hydro-climatological consequences of climate change.

The main conclusion is that water and vegetation reciprocity is an important key to sustainable (re)development at a landscape scale. From basic laws of biology, chemistry and physics it can be established that signal processing is reciprocal and related both to spatial architectural patterns and temporal frequencies, which must be managed in harmony.

From the literature studies as well as the model tests in the thesis it is also concluded that simple models based on synoptic indicators can perform as well as more sophisticated empirical or physical models. The concept of patterns, intelligible to humans makes GIS a strong candidate for encoding the symmetries between processes and landscape objects, and displaying model results for management and policy, and vice versa. The integrated models presented are comparatively simple and easy to use. They are thus useful for knowledge inference and hypothesis testing. They hold promises as management and policy tools in regions suffering from land and water shortages, for regions with poor data, and for regions where traditional models developed in temperate climates do not apply, and in times of transient changes. However, as all models they should not be used outside their scope. In many more narrowly defined cases, traditional models will be superior tools.

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NOTES

[1]The paper is written by the author of this study. However, it very closely follows the original ideas of prof. Ripl who commented and updated the manuscript at different stages, and reluctantly agreed to be first author on the request of the second author.

[2]The paper is mainly written by the author of this study, who also developed the tools and ideas presented (further clarified in the article).

[3]The paper is compiled by the author of this study, from an MSc degree work (Mahlander and McCarthy, 1995) based on the present authors' ideas and supervision.

[4]The paper is compiled by the author of this study, from an extension of an MSc degree work (Lindholm and Åkre, 1996) based on the present authors' ideas and supervision.

[5]In paper I efficiency is defined by suggestion from the ratio between cyclic processes and outflow losses (measured as proton flow), which resembles the concept of determined and undetermined information in ecological systems stemming from Margalef (cf. H.T. Odum, 1971).

[6]GIS are computer-based tools to capture, manipulate, process, and display spatial or geo-referenced data. They contain both geometry data (co-ordinates and topological information) and attribute data, that is, information describing the properties of geometric objects (see e.g. Burrough (1986) or Nyerges (1993) for introductions to GIS, and Maguire *et al*. (1991) for a most comprehensive volume on GIS).

[7]Lotka (a physicist by training) also first suggested thermodynamic efficiency to be the ultimate criterion for natural selection; his work can hardly be overestimated.

[8]Vernadsky also put forward the still very much debated view of the noosphere - the world controlled by human thought (from the Greek *noos* - mind), see e.g. Clark (1986), Naveh and Liebermann (1994).

[9]From the Greek *cybernetes* - steermanship.

[10]Entropy is a measure of thermodynamic orderness (from the Greek *entrepein* - to turn in).

[11]Albeit the studies of Odum are based on thermodynamics, notably energetic regulation within and between trophic levels, they rely on simplified causative and scale discretised assumptions.

[12]Autogenic, development generated by internal processes (e.g. species composition and competition) (from the Greek *autos*, self).

[13]Allogenic, development generated from outside (e.g. water, wind) (from the Greek *allos*, other).

[14]Forest ecological development can be separated into 4 phases; reorganisation, aggrading, transition, and steady state (Bormann and Likens, 1979; Sprugel, 1985), where the forest floor has a lag time of a couple of decades with increased organic matter decomposition and nutrient availability after clear cutting (reorganisation) before it starts accumulating organic matter and internalising nutrient cycles during the aggrading phase.

[15]The hypothesis of ecological stability as a dynamic process thus challenged the MacArthur pattern equilibrium theory.

[16]This view have recently been expanded to ecological economics in Costanza *et al.* (1993).

[17]Especially the East European tradition has emphasised the holistic approach (Petch and Kolejka, 1993)

[18]Biocoenose is sometimes used as a synonym for community ecology, and in this thesis the term coenotic structure is used for the smallest self sustained unit of the landscape.

[19]Other synonyms include site, tessera, landscape cell, biotope and landscape element (cf. Zonneveld, 1989, p.14).

[20]From the Greek *chore* - an area according to its place.

[21] Revisiting the study site of Dunne and Black (1970a and b) Engman (1981) could also show that subsurface flow was a much more important factor in runoff generation than the original study had revealed; which fuelled the discussion.

[22]Leaf Area Index is defined as the area of the leaves per unit ground area.

[23]With vegetation also having the capacity to conduct water to the surface from deeper layers.

[24]At a landscape scale the vertically closed cycle is created over evapotranspirating areas by incoming radiation being dissipated by latent heat flux (i.e. a low Bowen ratio), which leads to a slower warming of the atmosphere and the creation of a planetary boundary layer at low altitude (at less than 1000 m, compared to 2000 - 4000 m over dry land dominated by sensible heat flux). The smaller volume gets saturated with water, leading to precipitation in the afternoon (cf. Avissar, 1995). In fragmented landscapes such cool cells are destabilised, which lead to complex behaviour, speculated to promote excess precipitation by e.g. advection.

[25]Albedo, the fraction of incident light reflected from a surface.

[26]This process is continuous in cultivated soils (Sharply and Smith, 1983), and further enhanced by over fertilisation (Sharply *et al*., 1993).

[27]The concept of complex systems being composed of hierarchies stems from Koestler (1967), who labelled the discrete levels "holons", and the hierarchical system a "holarchi", terms that have gained some acceptance (e.g. Naveh and Liebermann, 1994). Koestler (1967) assumed the holon to have ontological validity (see note 38), whereas Allen and Starr (1982) and others have emphasised that they are just epistemological (see note 37).

[28]The boundaries are always functional, and usually also structural.

[29]The processes of life are all spontaneous; what life does is to concentrate, refine and separate the processes into order, in space and time instead of randomness.

[30]Naiman *et al*. (1988) discuss quanta in fluvial ecosystems.

[31]Norton (1996) discuss thoroughly the environmental policy implications of the hierarchical concept (notably as expressed by Holling, e.g. 1992), and suggests that it could be (logically) superimposed over human ethical and political values for a scalar Pareto optimality of sustainable development (in the sense of WCED, 1987).

[32]It is emphasised that at all scales a fraction of the water signal is internalised, leading to a fractal water cycle. In general, the fraction is higher on larger scales with an almost complete conservation of the global water cycle. This leads to a constraint put on lower scales by the slower (but more complete) turnover on larger scales.

[33]Asymmetries and overconnections (introducing a lag time), causes the recieving response to be out of phase upon signal arrival, illustrated for instance by pest outbreaks and large interannual fluctuations in predator-prey systems.

[34]Underconnected systems are not capable of transforming incoming signal streams into information (order); the signal escapes to other scales, illustrated for instance by losses of nutrients from cultivated catchments, causing eutrophication and growth in

the receiving waters instead. Human system interference is generally more inclined to cause underconnection than overconnection.

[35]In this thesis a patch is seen as a scale independent landscape unit, defined as an individual system relatively homogenous inside but separate from other adjacent patches; for example ecosystem, stand, field plot, marsh etc.

[36]Ecotones are usually defined as the boundary or transitory zones between adjacent ecological systems having a set of properties uniquely defined by space and time scales and by the strength of the interactions between the two systems. The emphasis put in this thesis is that ecotones are transitory zones with accentuated and accelerated gradients, often a result of human management of (at least) one of the two adjacent systems. In natural systems gradients are less abrupt (i.e. *ecoclines* - di Castri and Hansen, 1992).

[37]Study of validity, methods and scope of theories of knowledge (from the Greek *episteme* - knowledge).

[38]Study of the nature of being (from the Greek *ontos* - being).

[39]Published by the Stockholm Water Company as both abstracts and full papers, anonymous editor.

[40]Empirical figures have a very high variation, and thus are of no value as predictors (e.g. Hillbricht-Ilkowska *et al.*, 1995).

[41]In almost all cases the downstream flux is seen as the loss, except for water, where the part going back to the atmosphere (evapotranspiration) is seen as the loss. However, the vertical flow is the major carrier of the other losses, whereas evapotranspiration is closing cycles, driving photosynthesis and increasing system order.

[42]It is clear that if studying a soil column, field, or a catchment, the average loss will vary highly depending on the mosaic of the system under study. Soil columns in recharge areas are inclined to show the highest leakage. Losses are less in studies with fields as they also contain discharge areas, and in many cases further decreased when studying the whole catchment (Vitousek *et al.*, 1982; Karlsson *et al.*, 1988).

[43]In most cases the models are just using multiple bedded surfaces of the same co-ordinate system, with elevation as an adjoining attribute, and can thus more correctly be described as 2.5-D (cf. Gumbricht and Thunvik, 1996).

[44]Lately Imberger (1996) has shown, albeit for estuaries, that even the most elaborate mathematical models of water transport fail, even if divided into “infinitesimal” units, and heavily supported by data. With the introduction of biological processes, trajectories become unpredictable by present models.

[45]With many later descendent versions widely available for different GIS formats (cf. Gumbricht, 1992a).

[46]MCE developed as an alternative to traditional cost/benefit analyses. Accounted criteria are divided in constraints (i.e. forbidden areas) and weighted factors with continuous values (see Paper III). MCE s a goal driven method; the output of MCE is a ranked suitability map where the user (normally) must chose to allocate the objective(s) in a second step.

[47]Using a global data set with extensions over the last century, Tsonis (1996) discovered no change in average precipitation, but increases in variability in three quarters and a higher probability of extremes in later decades.

[48]From the Greek *heurism*, searching method, to find.

[49]From the Greek *tautologia*, repeating what has been said.

[50]The concept inspirations notably include the writings of Lotka, Lindemann, H.T. Odum and Prigogine.

[51]See note 18.

[52]Accuracy index adjusted for coincidence by chance.

[53]The hydrological effects of the suggested land allocation in Paper III has been reported elsewhere (McCarthy and Gumbricht, 1996).

[54]The model has been improved since the publication of Paper IV (Gumbricht *et al.*, 1996b). In later versions Leaf Area Estimation (LAI) is used (instead of NDVI) for depicting vegetation (LAI is commonly used in "big-leaf" models for coupling moisture fluxes to Global Circulation Models - reviewed e.g. in Lee *et al.*, 1993). The selection of LAI was based on a literature survey, presented in McCarthy (1996). Site storage was more clearly separated into an active dynamic (humic+biomass) and a passive constant (soil moisture) component, emphasising the sponge effect of vegetation in water holding capacity.

[55]See note 24 for the mechanism generating the fractal cycles. Within a stand the fractal water cycle is generated by amongst other things dew formation.

[56]At present calculated in the more powerful GIS software GRASS, based on three different algorithms (Szczepanek, 1995).

[57]An elaboration of this study based on five basins can be found in Gumbricht *et al.*, 1996b.

[58]A value of 1 indicates a perfect fit, 0 indicates that the forecasting is as good as averaging the time series variations to a mean flow.

[59]Homeostasis, the tendency of the environment to remain constant.

[60]The most widely spread mental image of Nature in pre-19th centuryWestern history is that of a "Great chain of being" (Lovejoy, 1936). Together with the idea of a benign Nature this has led to utopian ideals of societal organisation and living (Gumbricht, 1996c). It can be argued that environmental management is still largely influenced by those ideas. The barriers to overcome for reaching societal management and organisation (second order truth) in coherence with the scientific knowledge (first order truth), several mental barriers need to be overcome (cf. Gumbricht, 1993c).

[61]Which is surely the case were soils are covered with (thick) natural vegetation and humus layers (Hill, 1971).

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