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Watershed structure and symmetry with runoff and water quality

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ABSTRACT

Preliminary results of part of an ongoing Swedish-Polish research cooperation is presented. The aim is to identify managerial synoptic indicators of spatial structure that relate to runoff and water quality. Indicators are defined based on a concept emphasising the laws of mass conservation and thermodynamics, and the hypothesis of life as a dissipate structure controlling energy and water flow. All processes are regarded as reciprocal and linked over space and time, as opposed to traditional reductionistic cause-effect models. In the study Remote Sensing and Geographical Information System have been applied for encoding complex landscape pattern into robust indicators. Rule based contextual image analysis methods have been developed for categorisation of landscape mosaic structure according to the patch-ecotone perspective. Symmetry of structure and function is evaluated using simple statistics and pattern recognition. Application of logical and robust indicators for model parameterisation, and integrative management of watershed fluxes is outlined.

INTRODUCTION

Environmental research has focused on isolated issues (e.g. drought, floods, acidification, eutrophication etc.), which are dealt with as linear cause-effect problems. More recent findings have clearly proven nature to consist of complex feedback systems, changing in character over time and space (Gleick, 1987). However, the thus strong link between environment and society (cf. the Brundtland commission - WCED, 1987) is rarely considered in policy and management, with a few recent exceptions (cf. Grossmann, 1991; Fedra, 1993). And despite the political will, operational analyses of e.g. sustainable development have been few (Svedin and Hägerhäll-Aniansson, 1992). Water as a flowing resource poses additional problems (cf. Falkenmark, 1988; 1993), a possible explanation why it was laregely ignored by both the Brundtland commission and Agenda 21 (*ibid.*). However, the necessity of founding water management on natural water dividers is now widely accepted.

This article summarises the status of part of a joint research cooperation between the Royal Institute of Technology, Stockholm, the Polish Academy of Sciences, and the Cracow and Warsaw Universities of Technology. The program aims at creating integrative tools for spatial evaluation, modelling and, finally, management of watersheds. The management goal is to decrease the gap between parsimonious natural cycles and the wasteful human means of landscape exploitation and production.

Geographic Information System (GIS) and remote sensing (RS) are used as vehicles for spatial analysis and modelling (cf. Gumbricht, 1994).

Program scientific concept

The program is based on the holistic Energy-Transport-Reaction (ETR) concept (Ripl, 1993) that regards the watershed as a thermodynamic open system, where daily and annual pulses of solar energy are dissipated across interfaces under matter transformation. Life (i.e. vegetation) channels this energy dissipation, turning matter into living structures, thus controlling both energy flow and matter turn over. Life's control of its environment is accomplished through a hierarchical organisation of processes, interactions and interfaces (Fig. 1) (Allen and Starr, 1982).

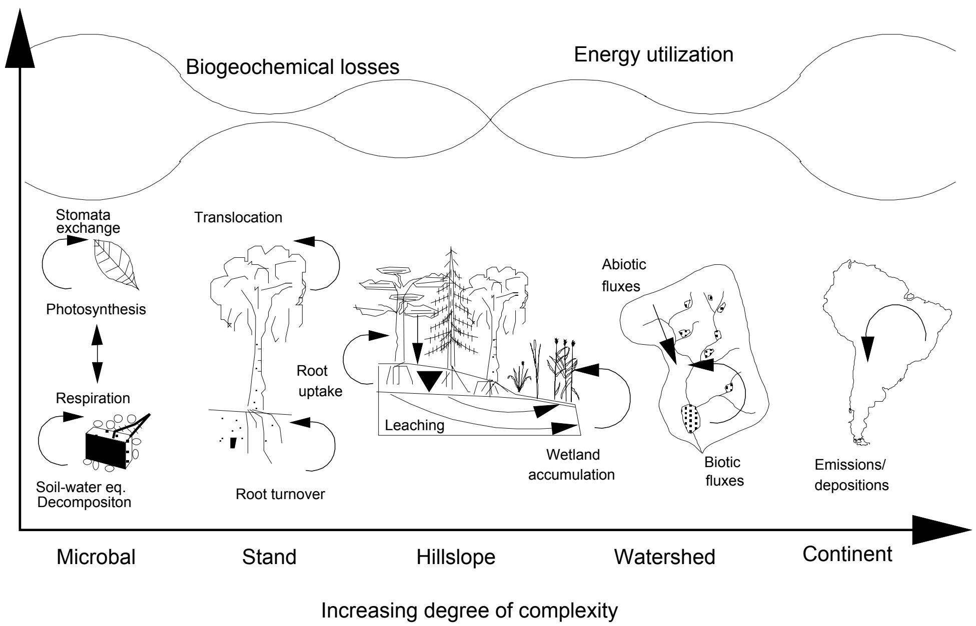

Figure 1. Hierarchical organisation of biological structures controlling energy dissipation. Major processes for closure of circuits at different spatial scales are indicated

Spatial pattern of biological structures controls site specific fluxes of energy and matter (including water) at any scale, including the watershed (cf. Bormann and Likens, 1979; Wiens *et al*., 1985). A competetive system is characterised by minimum irreversible losses, and a maximum of biological control of energy dissipation in a limited spatial domain over a limited time period (Fig. 2). There is a coherence between space and time limited processes that has led to reciprocity in structured (biological, non-spontaneous) processes (e.g. photosynthesis-respiration, dissolution - precipitation, evaporation - condensation). Water is thus the medium for controlling energy dissipation.

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As widely accepted, human cultivation and exploitation of the natural landscape causes the cyclic pattern of natural ecosystems (cf. Bormann and Likens, 1979) to break down, increasing matter, water and energy losses (e.g. Rast and Lee, 1978; Bosch and Hewlett, 1982). Empirical findings give sufficiently good evidence of lower nutrient and water losses from forested or mixed land use pattern compared to more homogenous arable and/or urban land use pattern (*ibid.*). However, the range of values indicate that simple area summation of different land cover classes combined with export coefficients is a rather weak predictor of e.g. cumulative nutrient losses. Landscape mosaic configuration (spatial juxtaposition of patches, corridors, and matrices) is a more sensitive and precise controller of functional processes (cf. Peters and Walling, 1991).

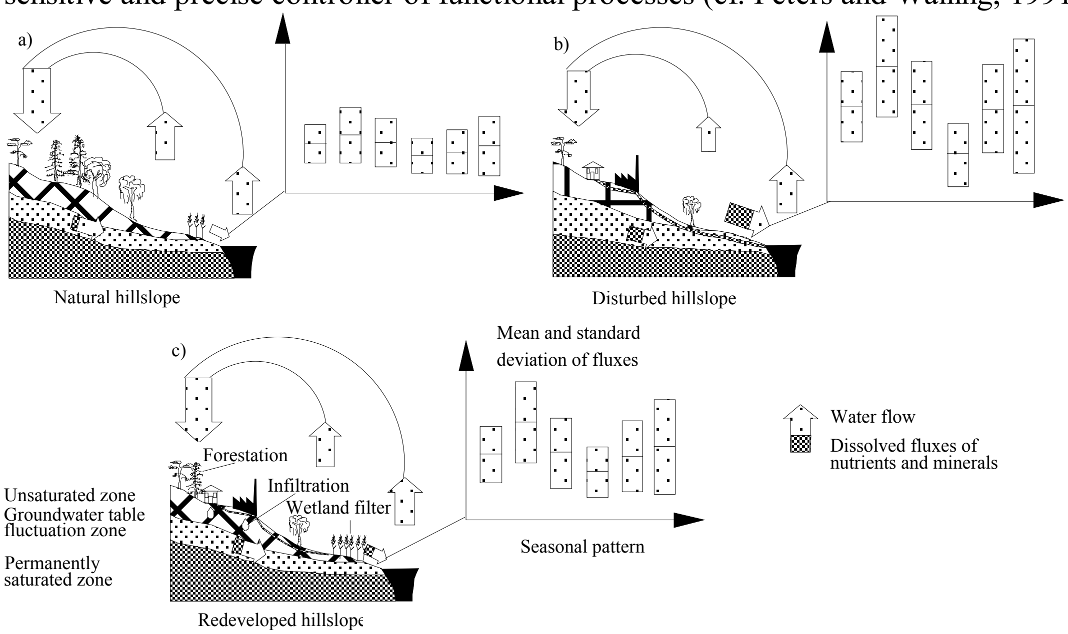

Figure 2. Schematic dynamics of water flow and dissolved fluxes in (a) natural, undisturbed landscape, (b) anthropogenic disturbed landscape, and (c) redeveloped landscape for minimum irreversible losses.

Based on logical deductions of the ETR concept combined with empirical results, the study seeks to define and evaluate indicators of spatial structure that relate to indices of integrated functions (runoff and water quality). Important structural parameters include hillslope pathways and gravitational gradients, as suggested by, *inter alia* the river continuum concept (Vannote *et al*., 1980), the nutrient spiraling concept (Newbold *et al*., 1981), and the division of hillslopes in source generating recharge area and accumulating discharge area (e.g. Richardson *et al*., 1992). As transition zones are major regulators of functions at a landscape scale (Wiens *et al*., 1985), the patch-ecotones perspective (Holland *et al*., 1991) is used in combination with flow path (i.e. ecotone crossings) along reliefs for defining logical synoptic indicators. Ecotones act as sinks, conduits, temporal smoothers or sources of fluxes; functions that change over time (Gumbricht, 1993a). The highly productive terrestrial-aquatic ecotone in general is a major barrier for water and nutrient fluxes, thus an important landscape element for sustainable redevelopment (Gumbricht, 1993b).

DATA SETS AND COMPUTER TOOLS USED

The primary study areas are the Ljungbyån watershed in southeastern Sweden, and the Krutynia and Jorka Watersheds in the Great Masurian Lake district, Poland. Landsat TM data was used for land cover classfication. Watershed and stream network delineation, and for Krutynia and Jorka also elevation, were manually digitised from maps in a scale 1:50 000. In Ljungbyån water flow is measured continously, and water quality is measured every second month at 14 stations. In Krutynia (at Ukta) and Jorka (mouth), monthly measurements of both flow and water quality were started in September 1993 and will continue until (at least) August 1995. Data manipulation has been done using the GIS GRASS (UNIX) and IDRISI (DOS). Programs for contextual and rule based image classifications, and statistical evaluation of structural and functional relations have been written in Pascal. A simple decision support system for extraction of spatial indicators was developed combining GRASS and UNIX by using C. The hydrological modelling was developed in STELLA and compared with the lumped hydrological HBV-model (Bergström, 1976).

METHODOLOGY

The program takes on a holistic system approach. Methodology is based on logical deductions from basic natural relationships (the ETR-concept) combined with empirical results of application to complex systems. It seeks simplification without reduction. It is emphasised that the concept hypothesis is possible to falsify (*sensu* Popper, 1972).

Fluxes of water and nutrients leaving the watershed over cyclic return periods are interpreted as integrated signals of system dynamics. The signal stream is turned into functional indices by calculation of mean and standard deviation for each period (e.g. month)(cf. Fig 2). Indices are then compared to indicators of spatial pattern derived from RS and GIS-calculations. The principle of Occam´s razor is applied to identify robust indicators relating to functional indices (Fig. 3).

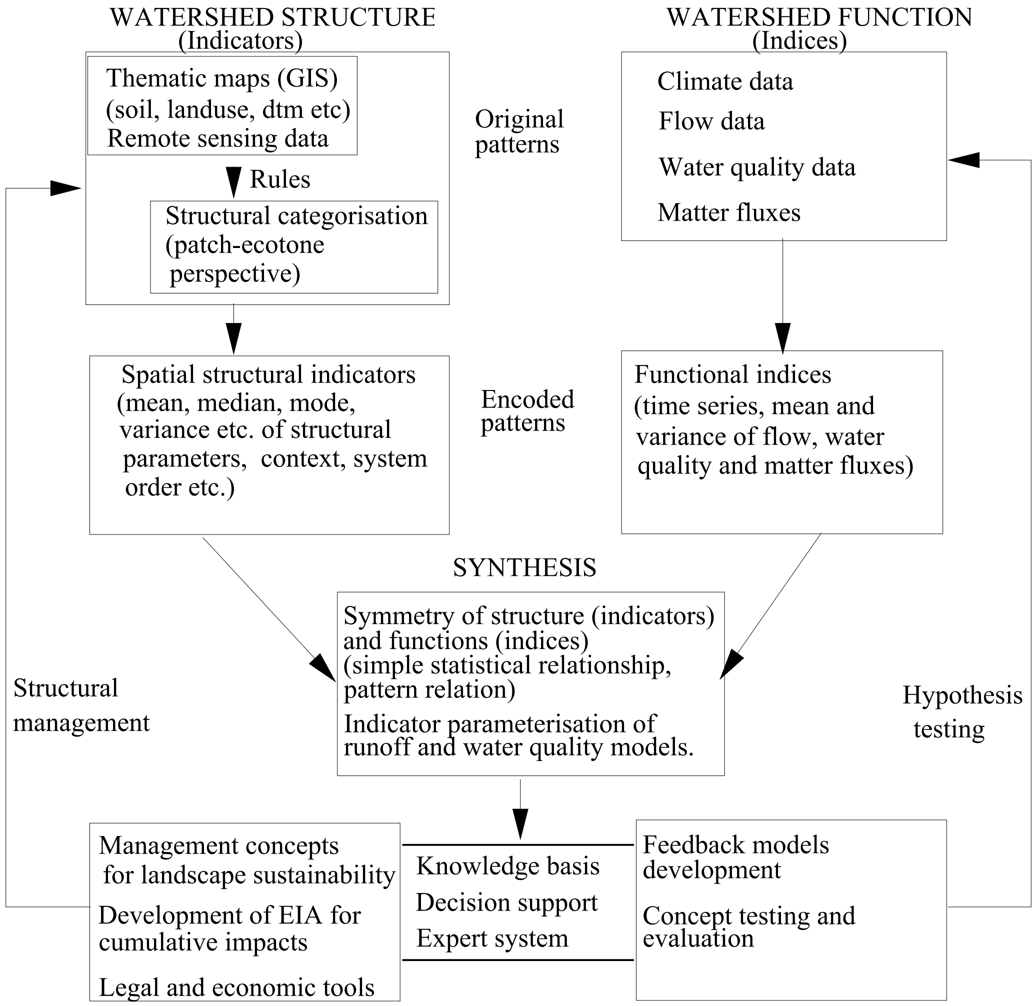

Figure 3. Summary of operational approach in the presented research program.

Matrix patches of homogenous ecosystems are satisfactory classified from remotely sensed spectral bands using traditional multispectral or rule based methods (cf. Argialis and Harlow, 1992). However, for tracing of edges and ecotones a contextual classification is hypothesised to be superior. A rule-based filter developed within the program considers poorly or unclassified cells from an *a priori* classification, and classifies those cells by comparing their spectral characteristics in the original bands with that of their already classified neighbours (Fig. 4) (Bernatek, 1995). The user define the allowed neighbourhood, as well as levels of acceptance regarding coverage of preclassified neighbours and statistical deviation of the spectral characteristics. The user can also consider alternative measures, *inter alia* normalised difference vegetation index (NDVI), for the categorisation of the unclassfied cells. Classification accuracy was tested against maps and field data (Bernatek, 1995).

5	5	4	5	6	9	9	9	×
×	×	4	4	4	9	9	1	1
7	7	○	4	4	4	1	1	1
7	×	×	4	4	×	5	5	5
7	7	×	×	×	5	5	5	2
7	7	5	5	5	×	2	2	2
7	7	×	5	4	4	2	2	2
7	×	5	4	4	4	2	2	2
7	7	5	×	×	4	×	2	2
7	×	5	5	×	4	×	2	2

× Unclassified
○ To be classified
1-9 pre-classified

Figure 4. Rule-based filter for contextual classification. The cell to be classfied need a filter size 5x5 if more than 5 neighbours are required for classification. In either case, prior class 4 will determine the categorisation of the cell to be classified.

Apart from traditional encoding of the original pattern into area distribution, also ecotone length distribution and flow length and flow path are seen as logical synoptic indicators, and encoded using GIS. Flow length (or flow route) is defined as the length a drop has to travel in the landscape before reaching a water body. Flow path is defined by the number of interfaces (ecotones) the drop has to pass on this journey. (Szczepanek, 1995).

The symmetry of spatial structure (indicators) and functions (indices) is analysed by using pattern recognition (cf. Fig. 7) and ordinary least square regression analysis (single and multiple). Logical indicators with a (hypothetical or empirical) high symmetry to functional indices are used for parameterisation of a lumped hydrological model - PATH, developed within the program (Wazniewicz, 1995). The model is based on vertical filling, storing and evapotranspiration. Groundwater is routed along the hillslope as a function of vertical water content, and overland flow occurs during heavy rainfall (Fig 5). Evapotranspiration is determined by degree of vertical storing and temperature, and is intended to be parameterised by distribution of e.g. NDVI. Hillslope routing of both overland and ground water flow is parameterised by using flow length and flow path, and part of the routed water is allowed to evapotranspirate. However, these terms have been held at unity during model development.

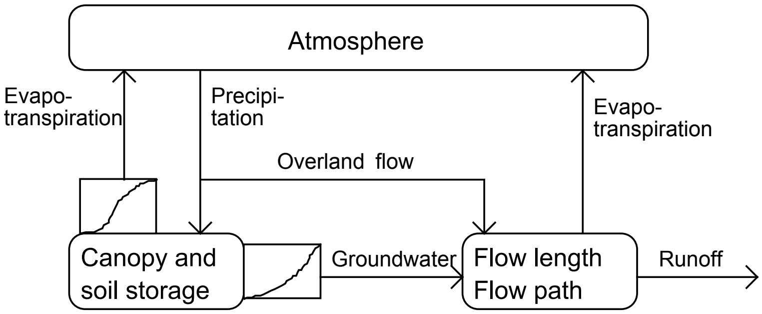

Figure 5. Concept of the developed lumped hydrological model (PATH). The model is outlined for parameterisation with synoptic indicators derived from GIS (see text).

RESULTS

The encoding of spatial structure is based on satellite data application of GIS. Different interpretation methods were tested for portraying the landscape patch-ecotone perspective. Using traditional multispectral (maximum likelihood) classification (Landsat-TM, bands 3, 4 and 7), overall accuracy for Krutynia and Jorka was estimated to be 76,8 % (Fig. 6) (Bernatek, 1995). The contextual filter was then applied to an image where pixels statistically classified with different accuracy threshold levels had been rejected. Classification accuracy decreased to slightly lower levels after applying the contextual filter (*ibid.*)

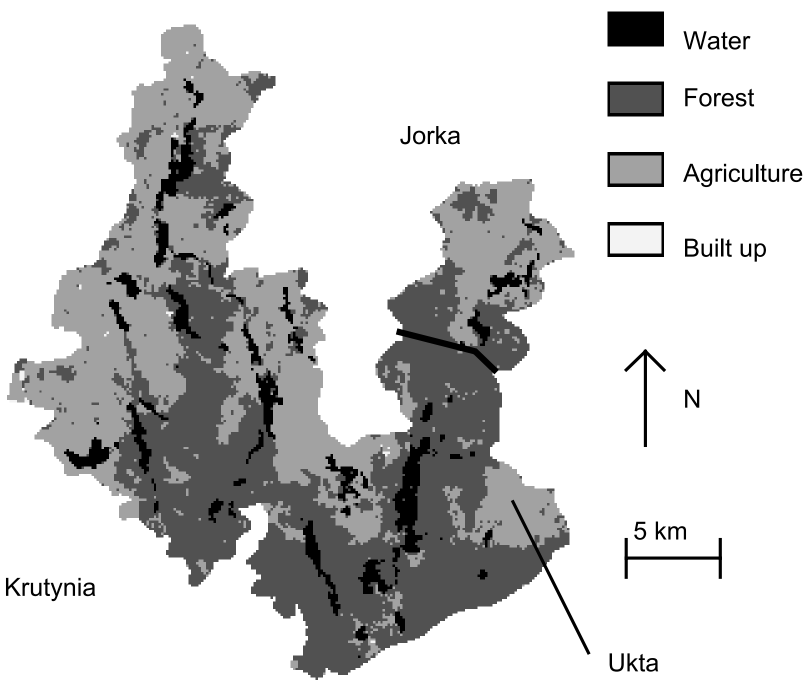

Fig. 6. Classification of land use/cover in Krutynia and Jorka based on a combination of multispectral statistical and rule-based contextual classification. Overall accuracy = 76 %

For Ljungbyån, only traditional multispectral classification has been applied so far (overall accuracy = 81 %). The time series from Ljungbyån has allowed evaluation of symmetry between structure and function. Indices for water quality were calculated for each month of sampling (Fig. 7) and compared with indicators for relative area distributions and ecotone lengths. Strong relations were found between exploited area (i.e. agriculture and built up) and losses of nutrients and dissolved salts (Fig. 7). Forests, wetlands and riparian zones acted as net sinks and dampers of fluctuations. Ecotones encompassing wetlands and riparian zones adjacent to agricultural land acted as barriers to nutrient transfer, whereas ecotones adjacent to built up area did not show any such effect.

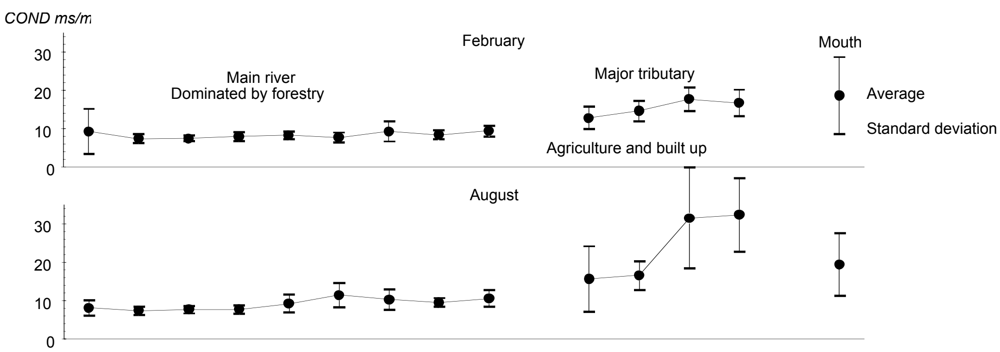

Fig. 7. Pattern relation of dissolved salt losses from Ljungbyån. Land use changes from foresty to agriculture along the river (see text). The pattern is based on data from 1984-1993.

Modelling of runoff has been undertaken for Krutynia and Jorka. The image of the watersheds (Fig. 6) was used for parameterisation of total area, lake area, and elevation distribution. After calibration the HBV model got an R^2 of 64 % for the period September 1993 - August 1994 (Fig. 8). The PATH-model got an R^2 of 62 % after calibration (Wazniewicz, 1995). To test model performances independently the parameterisation for Krutynia was used for Jorka, only changing the parameters derived from the image. The apparent difficulty due to a large area of perched aquifers was handled by reducing the area parameter of Jorka for both models to 1/3 of its digitised size. R^2 for HBV was then 50 % and for PATH 34 % (*ibid.*).

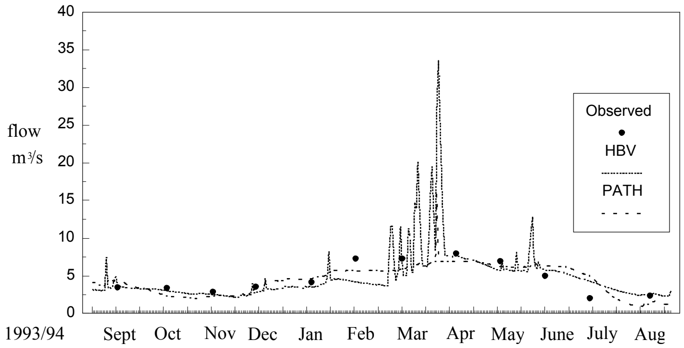

Fig. 8. Model performance of HBV and PATH for Krutynia waterhed (see text).

DISCUSSION AND CONCLUSION

During the last century man has changed the global pattern of land cover (Brouwer *et al.*,1991; Turner *et al.*, 1991). This has led to severe relaxation of spatial closure of energy and matter cycles at most scales, which the great floods that occured in the USA and Europe during 1993 are good examples for. The sustainability and viability of both small and large scale systems is thus threatened. Since it is difficult to decrease the total area used by man for agriculture, settlement and infrastructure, heterogeneity of landscape mosaics and spatial arrangements should form a holistic management (cf. Holland *et al.*, 1991). It is also clear that ecosystem redevelopment of natural systems must be implemented at all scales to be successful (Gumbricht, 1993b). This call for development of hypotheses and tools applicable for spatial management of complex structures, emphasising interfaces and variability.

The ETR-concept applied suggest an operational definition of landscape sustainability by regarding fluxes leaving the watershed as irreversible matter losses. Sustainable development is thus defined as minimum losses, with maximum efficiency when no losses occur (cf. Fig. 2). Models with robust and managerial structural indicators portraying essential system functions can be deduced and evaluated based on the concept. It is concluded that a holistic management must take its starting point in the water cycle, as water is the main mediator of landscape energy dissipation. The spatiotemporal process coupling, together with recent developments in integrating data, models and human reasoning, suggest a dynamic GIS as central vehicle for analysis and management (cf. Goodchild et al., 1993; Gumbricht, 1994). However, several problems remains to be solved.

Classification of landscape structure from remotely sensed imagery is well developed for homogenous area. The categorization of structural patterns, mosaics and corridors is more difficult (Johnston and Bonde, 1989). The contextual filtering developed and tested within the program did not show any improvement in overall classification accuracy. However, the *a priori* classification was done by identifying training areas on (out of date) traditional maps in the scale 1:50 000, and field data was not sampled with regard to structural pattern. Further development is necessary. One route is to use the filter for iterative reclassification of edges already detected in an *a priori* classification. Allowing the user to set hierarchical rules for categorization through a graphical interface is another. Both should preferably be accompanied with application of fuzzy logic to quantify errors and uncertainties.

Symmetry evaluation between structure and function showed the well documented relation of higher nutrient and salt losses from exploited areas, and damping effects of dense natural vegetation (cf. Rast and Lee, 1978). The results indicated that ecotones in natural systems facing agricultural areas had a significant effect on reducing both overall (average) losses of nutients, as well as damping the fluctuations. The same pattern was not found for ecotones adjacent built up areas which can be hypothesised to depend on exportation of surplus energy and matter through pipe systems instead of into the terrestrial environment.

The hydrological watershed model developed is based on the patch-ecotone perspective (Holland *et al*., 1991), emphasising vegetation and the atmosphere-vegetation-soil interfaces (cf. Kienitz *et al*., 1991) as major flow regulators. This is a new approach compared to traditional (white box) models where soil conditions are the main regulators (Gumbricht, 1992). The first version of the model reported herein was used to model flow in two Polish rivers. However, without using the calibration based on synoptic indicators that was intended. Potentially the model could have made a better prognosis for Jorka; the perched aquifers means that both flow length and flow path would have been higher than for Krutynia, thus increasing evapotranspiration. The result of appropriate parameterisation will be tested in the near future. Model development and testing will also include other regions.

Applying integrative indicators reflecting hillslope processes opens for a more physical and thus managerial parameterisation of hydrological and water quality models, as compared to the empirical status of traditional models (*ibid*.). In this study flow length and path dependent on relief and system order respectively were suggested for parameterisation. Ecotones are potentially managerial entities in the landscape changing primarily the flow path. Thus ecotones could be used for integrated hydrological and water quality management. Especially wetlands and riparian forests suggest themselves as strong candidates for management (cf. Gumbricht, 1994). Finding logical positions for wetlands in the watershed, and designing them accordingly composes the second half of the presented research program.

It must be kept in mind that the spatial scale is inherent in the definition of landscape heterogeneity and diversity (Fig. 1). Discretising the system at a certain scale means disregarding all other scales, i.e. inferring errors in models. Potentially this error can be quantified by applying fuzzy logic, which hence is a prioritiesed task.

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