Project in Natural Resources Management

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IDENTIFICATION AND MANAGEMENT OF INTEGRATED LANDSCAPE RESOURCES - CYPRUS, NICARAGUA AND SWEDEN

Introduction

Human changes of the landscape have been accelerating since the onset of the agricultural revolution (Turner et al., 1990). By introduction of fossil fuel energy in e.g. agriculture and forestry the changes have become world wide. This has led to more open landscapes where weathering, erosion and water transported outflow is emptying the soils on vital components (Fig. 1). The natural landscape dominated by a vertical water cycle and with low matter and charge losses has been replaced by a hot bleeding landscape with polluted water production (Ripl, 1995; Gumbricht et al., 1996a[1]). There is a preferential transport of nutrients, leaving poisonous metals and inert bulk material in the soil. The tight communication in the natural landscape is loosened and biological control of energy dissipation decreased. The present landscape must be restituted; cyclic matter flow must be restored, and water flow and quality stabilised. The river and its valley form an integrated part nested to other scales leading to non-linear functions. Understanding and managing this complex system must thus be holistic using heuristic perceptive principles, and simple and transparent models relating patterns and processes.

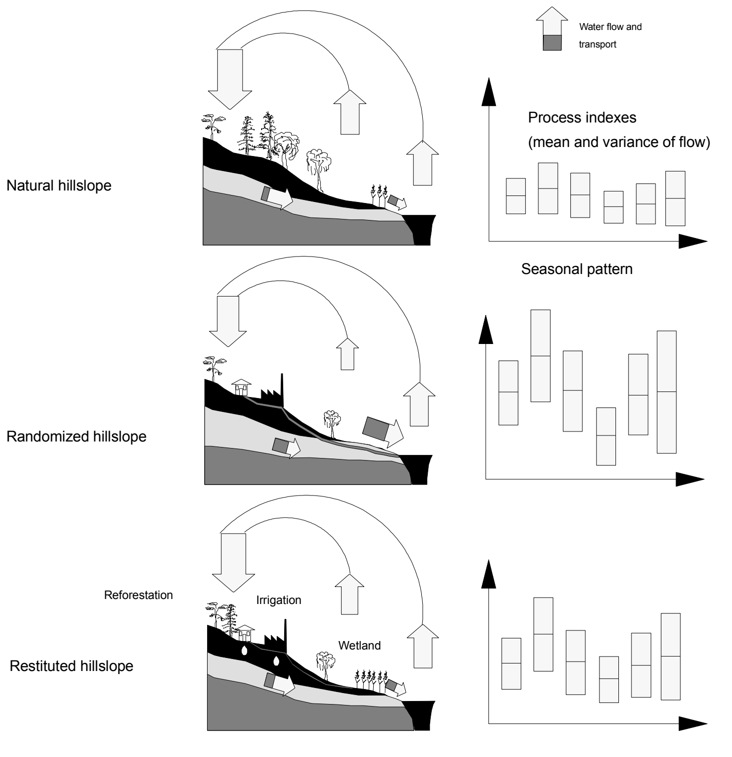

Fig 1. Schematic image of hillslope structural patterns and relating functional indices.

The watershed is a thermodynamic open system, where daily and annual pulses of solar energy are dissipated under matter transformation. Through energy dissipation ordered structure (life) evolved (cf. Prigogine and Stengers, 1982). In natural landscapes living structures have closed matter flow in local cycles by control of energy dissipation. The

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biological control of energy dissipation is accomplished through processes in the water cycle: evaporation-condensation, photosynthesis-respiration, dissolution-precipitation (Ripl, 1995, Ripl and Gumbricht, 1995[2]). These processes are reciprocal and linked over space and time. The energy processor properties result in dynamic equilibrium patterns of temperature, precipitation, runoff and subordinate chemical processes with respect to space and time. E.g. what is evapotranspirated at one time and place, must be condensed and precipitated at another.

Energy dissipation occur exclusively over interfaces, and life can be seen as a hierarchical organisation of interfaces (cf. Allen and Starr, 1982; O´Neill *et al*., 1986). The hydrological cycle can thus best be described as a fractal cycle, where internalisation of water increases as more interfaces are included in the scale of observation (Fig. 2). An efficient system has a maximum control of energy dissipation over limited space and time domains, resulting in minimum matter and water losses. A sustainable system (e.g. landscape) is hence characterised by efficient communicating biological structures, and stable production of clean water. Major structural components are patches of ecosystems and their intermediate gradients - ecotones (Holland *et al*., 1991).

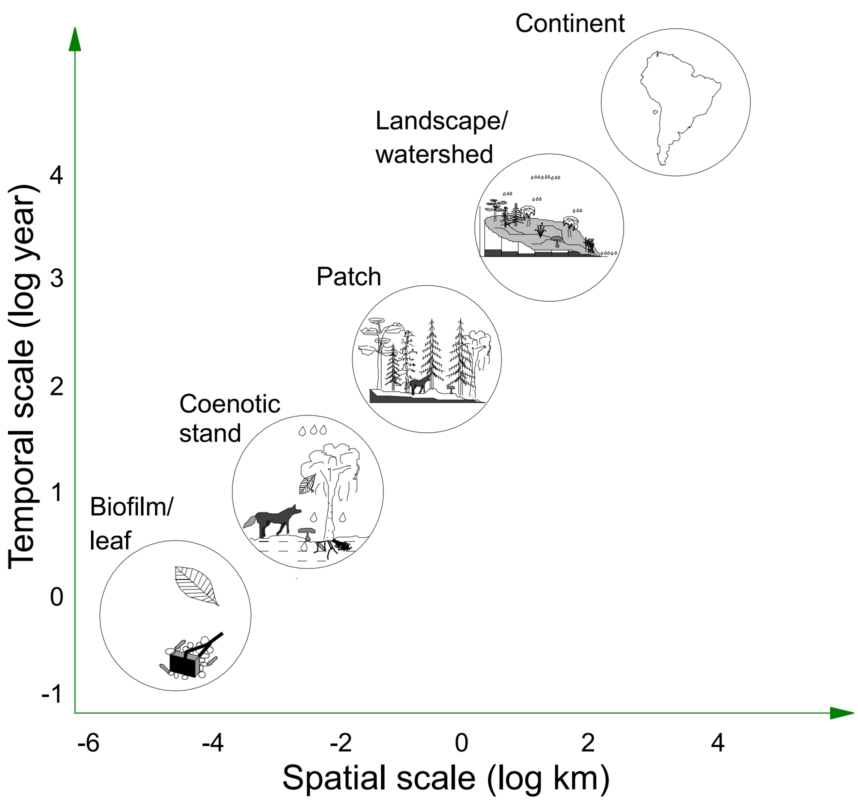

Fig. 2. Hierarchical organisation of biological structures controlling energy dissipation. Major processes for closure of circuits at different spatial scales are indicated

It must be concluded that water management can only be based on a holistic landscape approach. The spatial arrangement of land cover, its mosaic structure and interface characteristics determine the water cycle (and thus all other subordinate processes). Land and water management must hence be integrated. The complex spatial arrangement and the dynamic processes call for applying geographic information systems for identification of

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relations and implementation of a holistic management (Gumbricht, 1995; Gumbricht et al., 1996a).

Environmental modelling with GIS

Recent progress in Geographic Information System (GIS) has drawn upon decision making under uncertainty applying concepts of fuzzy set, multi-criteria methodologies and dynamic modelling. Communicating imprecision and error, applying fuzzy logic, and involving human participation in heuristic decision making, holds promises for the future applicability of GIS for natural resources management (cf. Lolonis and Armstrong, 1988; Fedra, 1993; Gumbricht et al., 1995b[3]). However, further development of tools for approximating human reasoning and enhancing the level of artificial intelligence (AI) in GIS is a necessary step before spatial arrangements in the landscape can be wholly analysed in a GIS environment (cf. Burrough, 1986; Ripple and Ulshoefer, 1987). GIS is presently being integrated to various other fields of science using computer vision as an interface to the user (e.g. Goodchild *et al*., 1993; Fedra *et al*., 1992). The GIS-integration has its furthest development towards remote sensing (RS) (Ehlers, 1992), leading the way to a new discipline of geo-informatics (synonyms: geographic information science, geomatics).

Models in general can have one of two aims: to improve the understanding of real world processes, or forecasting future events for improved decision making. Traditionally models are defined as scaled, conceptual or mathematical, where the mathematical models have the widest use in environmental modelling (cf. Goodchild et al., 1993). These models can be further classified as deterministic or stochastic. Both types can be either time invariant (steady state) or time variant (dynamic). Models in GIS obviously have a spatial dimension, and are said to be distributed (or semi-distributed) as opposed to being lumped over large regions. There is also a trend away from lumped models towards models favouring distributed parameters with physical interpretability. Part of the drive behind this development has been the belief that the sequential task of dividing a landscape into smaller units will allow non-linearities and spatial variability to be predicted. This development has just been partly successful (Beven, 1989; Moore et al., 1993).

Environmental models applicable for GIS vary from plot size to global circulation models (GCM). Time steps in such models goes from minutes to years. However, with a few exception GIS is at present a static descriptive tool unable to handle simultaneous changes in multidimensional fields. It is mostly used as a storage and display medium and for parameterisation of models formulated based on old Newtonian concept. Present state of development is building nested models (addressing both complex spatial and temporal scaling problems), using GIS for parameterisation of subgrid processes or the aggregation of properties to a grid level (cf. Godchild et al., 1993). This is now widely adopted for coupling water and energy budgets of GCM and physically based mesoscale. Models for energy and water budgets controlled by vegetation conductance of water include the simple biosphere model (SiB), the Biosphere Atmosphere Transition Scheme (BATS) and the Land Ecosystem Atmospheric Feedback (LEAF) (summarised in Lee et al., 1993). They rely on distributed parameters for vegetation cover (i.e. Leaf Area index - LAI) derived from satellite imagery. Avissar (1993) suggested an alternative approach using a probability density function for subgrid parameterisation as an alternative to those numerical models.

Data structures in GIS

The data in GIS represent either “fields” (e.g. elevation, groundwater level, soil class, spectral reflectance) or discretised “object” classes (e.g. lakes, cities, states). Most natural phenomena are of field character, whereas anthropogenic structures and definitions are object-oriented (Goodchild, 1993). In GIS, data can be arranged in various ways, basically coming down to the previous dichotomy of either raster (or rectangular **pic**ture **el**ements - pixels) or vector representation (*ibid*.). However, the two formats are increasingly integrated in software

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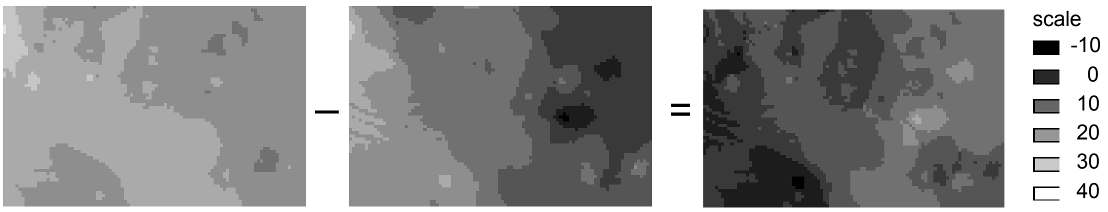
packages. Object data is naturally vector related with present developments being towards fuzzy encapsulation, inheritance and identification. This development seems especially important for more complex data sets including those that are three-dimensional.

Another development in data modelling is towards fuzzy representation of data where a position or object can have membership in several classes. For instance, a lake shore can be both land and water, or a park can be both a forest and a grassland (where membership can be defined based on tree density). A non-trivial task is to quantify errors and error propation in such data.

<u>*3D data sets*</u>

3D GIS (or Geoscientific Information Systems - GSIS), are tools for the investigation of surfaces such as hydrogeological features (e.g. Raper, 1989; Faunt et al., 1993; Fisher, 1993). Most present 3D GIS are extensions of 2D GIS, adding the depth (z) dimension through multiple isometric bedded surfaces of the same x-y-co-ordinate system and resolution (Raper, 1989). This quasi-3D approach cannot represent three dimensional surfaces like foldings and faults, but may be adequate for homogenous aquifers and simpler stratigraphies. If data are in a rectangular grid square (raster) format each 3D cell is called a voxel (i. e. from **vo**lume pi**xel**). This data format is well suited as input to finite difference models. More advanced models such as discrete fracture network models (usually based on finite elements) must be based on more advanced 3D GIS models. Gumbricht and Thunvik (1996) present a tool for creating 3D hydrogeological framework models combing 2D horizontal data with profile data (Fig. 3).



a) ground water table (m.a.s.l.) *b) bedrock surface (m.a.s.l.)* *c) ground water depth (m)*

Fig 3. Images over the Vassmolösa esker (SE Sweden) generated by the 3D hydrogeological framework model presented by Gumbricht and Thunvik (1996).

<u>*Spatial relations*</u>

Spatial relations between objects have three main forms:

- hierarchical relationship between simple objects that comprise more complex objects (e.g. points forming a line, or trees forming a forest),

-geometrical relationship between objects (e.g. distance, connectivity, adjacancy)

- morphological relationship (e.g. upstream of, communicating link).

Indexing and numerical portraying of spatial relations for furhter analyses is under strong development (McGarigal and Marks, 1993), especially in fields, such as hydrology and landscape ecology, where such relations have traditionally been used in modeling (Turner and Gardner, 1990; Moore et al., 1993).

<u>*Digital elevation models*</u>

Digital elevation models (DEMs) can be used to generate more than 20 indices of the land facet and its geomorphology (Speight, 1980; Moore et al., 1993). A simplifying assumption is that the upstream area can represent the amount of water passing a cell or point. Especially the empirical algorithms for antecedent soil moisture conditions suggested by Beven and Kirkby (1979) and O´Loughlin (1981), and indices of slope length and transport capacity (e.g. Moore and Burch, 1986) have led to widespread applications. The use of digital elevation data in modelling surface and near surface hydrology and erosion, is hence well established (DeVantier and Feldman, 1993). However, both flow routing and the calculation of upstream area is very dependent on the quality and resolution of the DEM, and on the algorithm used (Moore et al., 1993; Stenström, 1997).

Map algebra and cartographic modelling

With multiple bedded data, GIS is a powerful tool for map algebra (cf. Fig. 3) and cartographic modelling (Tomlin, 1990; Berry, 1993), a development rooted in McHarg's (1969) transparent map overlays. Early applications based on map algebra (i.e. site specific overlay analysis) in environmental modelling include assessment studies, where the vulnerability assessment of groundwater by the DRASTIC method has been widely adopted to GIS (e.g.- Lindström and Scharp, 1996). Risk evaluations (e.g. of salt water intrusion - Lindberg et al., 1996) (Fig. 4), and identification of source areas (e.g. of diffuse pollutants - Sivertun et al, 1988) are also common examples. With improvements in cartographic modelling, spatial relations (see above) have been adopted, for instance in erosion modelling based on the empirical and static Universal Soil Loss Equation (USLE) (Pilesjö, 1992; Wilson, 1996). The derivation of homogenous response units (HRU) based on multiple embedded data-layers is a more recent development (Flügel, 1996).

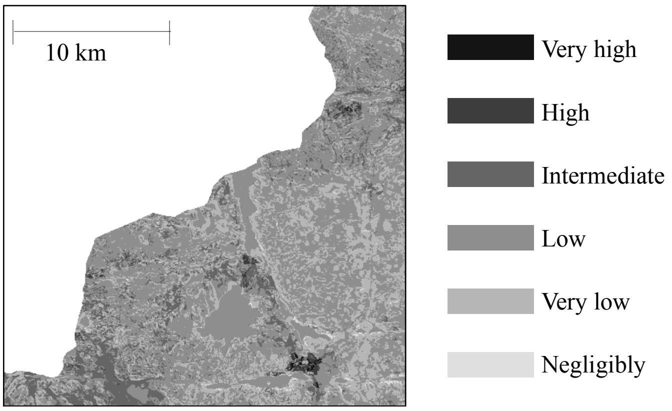


Fig. 4 Risk values for saltwater intrusion (E. Sweden) (adopted from Lindberg et al., 1996).

<u>*Mapping groundwater pollution potential*</u>

One of the most widely spread applications of static resource assessment in GIS is mapping of groundwater vulnerability using the DRASTIC index. The DRASTIC index essentially is a multi crieteria evaluation with the following factors (Appendix 4):

Depth to groundwater (m)
Recharge (mm/year)
Aquifer media
Soil media
Topography (slope in percent)
Impact of vadoze zone
Conductivity (transmissivity in m^2/s)

Each factor has a given weigth (determined to fixed values by a panel of experts), and also the factor scores are preset from physical values. The *apriori* definitions makes DRASTIC more of an expert system than a decision support tool, but its technical construction is exactly like that of MCE.

Representation of dynamics in GIS and model coupling

Dynamic processes can be coupled to GIS either as a superimposed function over the whole study area (dynamic maps - Grossmann and Eberhardt, 1992), or as an area dynamics dependent on site specific and topological relations. The dynamic map approach is commonly used for nesting large scale models (e.g. Global Circulation Models for climate scenarios - Lee et al., 1993; Hay et al., 1993) with smaller scale models of hydrology (Nemani et al., 1993) and ecology (Schimel and Burke, 1993). The smaller scale models can in turn be used to generate area dynamic processes for sub-grid parametisation of the larger scale models (e.g. Lee et al, 1993; Moore et al., 1993; Avissar, 1993). Most of the models use Leaf Area Index (LAI - defined as the leaf area per unit ground area) as an important parameter relating to stomata processes. NRC (1990) emphasised water-energy-vegetation interaction as a key in understanding climate and water systems.

The coupling of dynamic models to GIS has previously relied on loose coupling, where outputs have been transferred between the different models. Thus the strongest development has been in using GIS for parametising distributed models, and for displaying model input and output. This approach puts less demand on the model developers and programmers, but is flexible for those who master GIS (cf. Fedra, 1993). In most cases GIS is thus used as a static tool for map algebra. The present development is towards sharing the GIS data formats in an intermediate coupling (Ehlers et al., 1989; Tim and Jolly 1994). This is a common approach in more physical models of erosion (Kniessl, 1980), surface hydrology (Gumbricht, 1996) or ground water flow and transport (Gumbricht and Thunvik, 1996). Fig. 5 show the principles of a system hydrological model developed by Gumbricht (1996) and its coupling to GIS for parametisation. In urban environments vector GIS is used in this way as a standard tool for analysing storm drainage and piped flows (e.g. Djokic an Maidment, 1991; Elgy et al., 1993). The most advanced coupling should be seamless, with the model embedded in (or embedding) a GIS. Operative examples include the hydrological SHE model (Abbot et al., 1986) and the LISEM erosion model (De Roo et al., 1996).

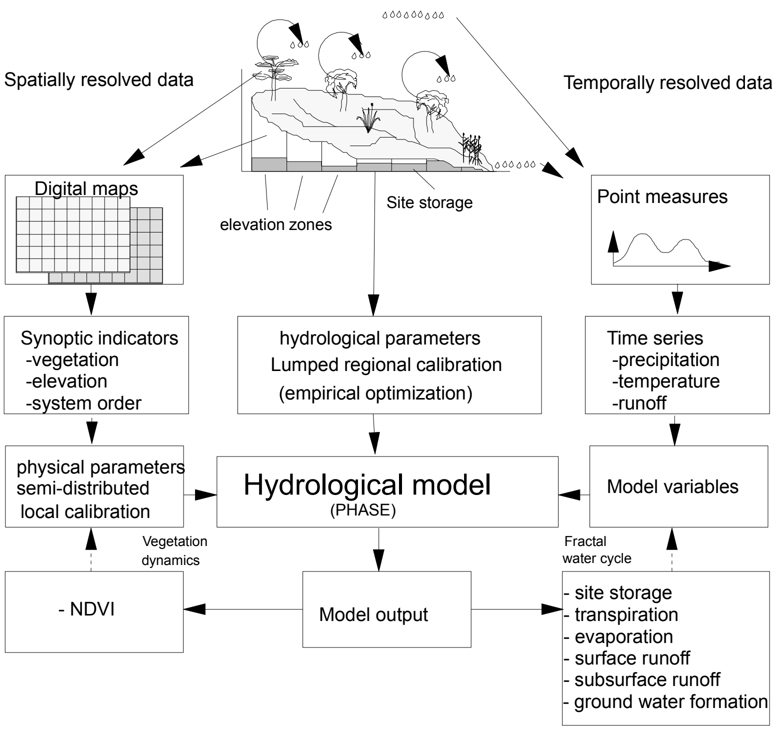


Fig. 5 Schematic relation of landscape spatial structure and hydrological functions as interpreted in the hydrological system model (PHASE) developed by Gumbricht (1996). The model is regionally calibrated by lumped hydrological parameters for soil moisture accounting and routing. Local calibration is 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.

Also the most elaborate models are crude simplifications of the real world. And as argued above, parametisation of present models overlooks the problems of scale and uncertainty. There are several reasons for uncertainty in model results: (i) only a limited number of processes can be related, (ii) processes may not be well understood, or for some other reason, maybe treated inadequately, and (ii) the spatial and temporal resolution is inadequate. Also the solution may be very sensitive to initial conditions if non-linear interactions exists (Lorenz, 1963). Thus there is a development towards transparent system models based on key relations, but with less focus of physical (reductionist) process elaboration. The model (PHASE) presented by Gumbricht (1996) is regionally calibrated using 3-7 parameters, with physically based key indicators of vegetation, size and elevation automatically extracted from GIS when applied to a specific basin (Fig. 6). The underlying assumption is that synoptic indicators for lumped sub-grid parametisation is a more robust approach. The model has shown robustness in transferability in parameter setting when applied to data sets covering Cyprus (Gumbricht et al., 1996a) and the Himalayas (Gumbricht et al., 1996b).

Hydrological modelling

Early views on rainfall-runoff formation assumed overland flow generated by water saturation in the top most soil, thus adding a storm flow peak to a base flow (cf. Gumbricht, 1992[4]). The contributing area of storm flow was later thought to be bound to wet areas, and lower slope positions, that could expand or contract due to moisture conditions. Using isotope studies it was discovered that most water flowing in streams had passed the soil, thus theories of subsurface flow emerged. It is now obvious that flow generation differs according to climate, land use and land cover, and vegetation, but that natural areas are dominated by subsurface flow. The fast response in rainfall-runoff subsurface flow has led to theories of macropore flow and vertical conductivity distribution. Concepts of runoff generation have thus focused on soil moisture and soil properties, disregarding vegetation and humic substance. However, recent findings and concepts suggest that vegetation and its products are the most important controllers of fluxes and energy dissipation across the atmosphere-land surface boundary (cf. Kienitz et al., 1991; Avissar, 1993; Gumbricht et al., 1996a). And that water is the dynamic medium through which this control takes place.

Continuous simulation conceptual models, based on a soil-moisture accounting routine as central percept, represent the present state of development of lumped parameter models in hydrology (cf. Gumbricht, 1992). However Gan and Burges (1990a; b) showed that these kind of models were not able to describe runoff processes in an idealised hillslope, and concluded that they were unsuited for modelling watershed hydrological behaviour. Wood et al. (1988) suggested a representative elementary area (REA) to handle nonlinearities in hydrological modelling by dividing the landscape into homogenous functional units. This has been adopted in GIS coupled hydrological modelling by the introduction of the Hydrological Response Unit (HRU) (Moore et al., 1993). A parallel path of development has been to build distributed hydrological models for hillslopes (TOPMODEL- Beven and Kirkby, 1979) and watersheds (SHE - Abbot et al., 1986), and creating GIS interfaces to such models (cf. Maidment, 1993). These models have topological connectivity, but no area definition or contiguity. They contain the same problems as the lumped models, but at a subgrid scale, and should thus need grid resolved data for calibration (Beven, 1989). This has led to an index approach based on simplified representation of the underlying physics of the processes but including the key factors that modulate system behaviour (such as vegetation and topography) (cf. Moore et al.,

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1993). A model based on those principles (PHASE) has been developed by Gumbricht (1996[5]), and shown good results in both independent time periods and watersheds (cf. Hessling, 1995; Gumbricht et al., 1996[6]). Elevation segments are filled by precipitation and water content is partitioned to evapotranspiration and runoff based on vegetation and soil conditions. The model uses GIS and RS for automatic physical parameterisation, and is calibrated using 3 to 5 empirical soil parameters.

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Digital image classification

Digital satellite images have become an important source of information for identification and management of land and water resources. Identification is usually done by classification into categories that are relevant for the user. Classification is based on the varying reflectance characteristics in different wavebands of the features to be categorised. An example of this type of classification is the creation of a digital landuse map from e.g. Landsat images. Recent progress in digital image classification has drawn upon rule based and contextual classification, also incorporating uncertainty (Gumbricht et al., 1995a[7]). Good summaries on digital image classification methods can be found in e.g. Curran (1985), Lillesand and Kiefer (1994), Argialis and Harlow (1990), and Bonham-Carter (1994).

Commonly, the interpretation of a satellite image is done by a pixel wise spectral classification with the use of some selected wavelength bands and a multi-spectral classifier, e.g. maximum-likelihood classification (Figs. 7 and 8). Although Landsat images represent the reflectance property of various objects, there is no unique correspondence between objects and their spectral signature. Different objects may have very similar signatures, while objects of the same type may have quite different signatures (Wu *et al.*, 1988). This indicates that conventional interpretation of satellite images can be very difficult since the spectral overlap between different classes may be so large that the overall accuracy of the classification is unacceptably low. Ancillary data such as digital elevation models and maps showing soil and geology can then be used to improve the classification (Argialis and Harlow, 1990). However, the complementary data have to have a known relationship to the classes in the image. This means that the classification is extended with a further decision making process, based on the knowledge of this relationship (Middelkoop and Janssen 1991).

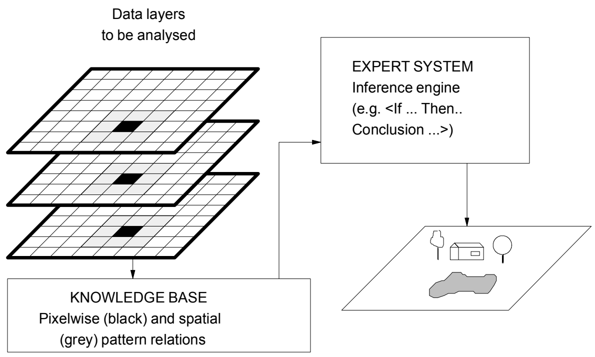

Fig. 7 Expert system image classification

Recent development in signature pattern recognition has been towards deterministic modelling of scene characteristics based on physical laws of radiance and energy balance, and using knowledge based classification with combined sources (cf. Argialas and Harlow, 1990). In a knowledge based classification ancillary data and knowledge are combined with spectral information. Relations must be known (or hypothesised) and inferred via e.g. an expert system (ES) engine (Fig. 7). Knowledge acquisition is a bottle neck, and the most subjective part of an expert system (cf. Robinson and Frank, 1987). Examples of knowledge representation include forward reasoning Bayesian classifiers with certainty factors (Wu et al., 1988; Srinisavan and Richards, 1990), application of markov chains and probabilistic transitory matrices (Middelkoop and Janssen, 1991), and discriminant analysis based on multiple signature and texture measures (Dymond and Luckman, 1993). Recent ES development for image interpretation include compact and transparent rules, natural language user interfaces, inclusion of fuzzy membership functions, and symbolic approaches mimicking human aerial photo interpretation (Dymond and Luckman, 1993; Leung and Leung, 1993; Srinisavan and Richards, 1993).

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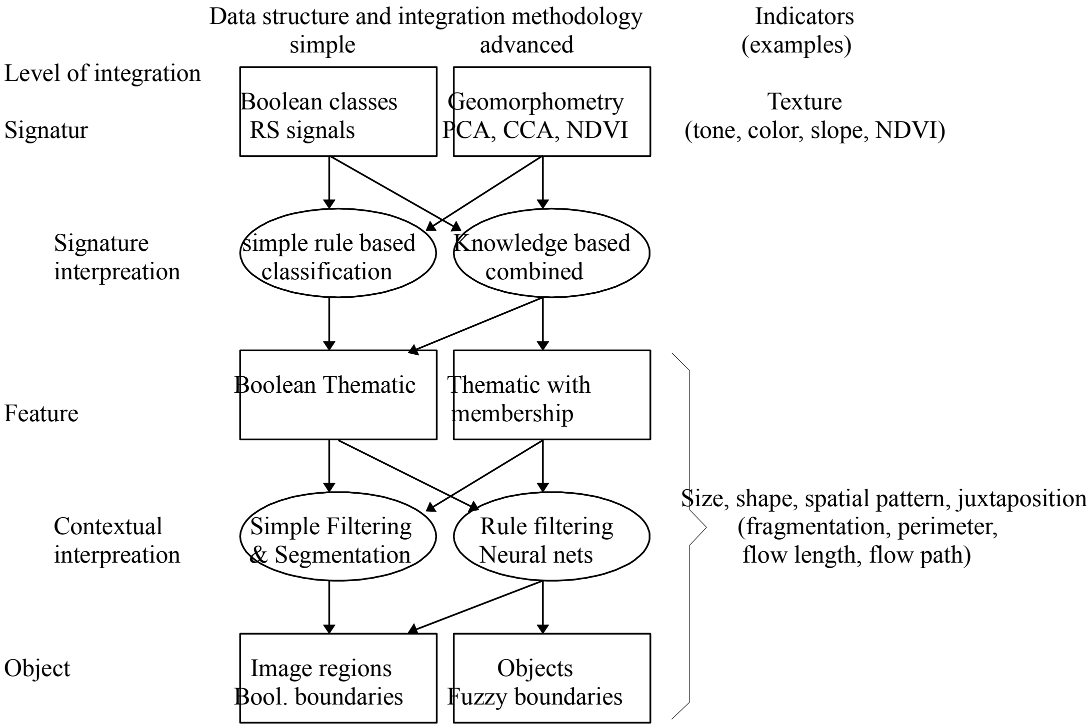

Fig. 8 A simplified scheme for image classification methodologies.

The pixel wise approach can not account for spatial patterns (e.g. roads, airports, drainage system). The state of image interpretation is thus towards using a high level approach employing domain specific knowledge of spectral, spatial and temporal properties (Fig. 8). Statistical knowledge filtering (e.g. Franklin and Peddle, 1989; Flygare, 1993), and rule based segmentation (e.g. Janssen et al., 1992; Johnsson, 1994) have been widely applied for spatial knowledge inference. More advanced structural models are based on defining primitive pattern elements (edges, lines, curves, angles) and relations that combine those elements. Artificial neural networks are well suited for learning such pattern relations. Application in image classification have mostly used back propagation, i.e. iterative updating of network hierarchical connection weights based on training set data (Hepner et al., 1990; Civco, 1993; Ryan et al., 1993). Neural networks hold promises for improved classification, even if they are still in their infancy. Reported successful applications include land cover classification (Hepner et al., 1991; Dreyer, 1993) and shoreline extraction (Ryan et al., 1991).

<u>*Digital image enhancement*</u>

Much of the work with digital image interpretation is related to enhancing characteristics of the features that are to be identified. Image enhancement include simple methods like contrast stretching and colour display, but also more advanced data compression techniques, multispectral enhancement, band to band rationing and subtraction, spatial filtering (see e.g. Curran 1985 for an overview). Initially the selection of wavebands is important for the interpretation. The spectral wavebands have different properties according to table 1.

Table 1 Landsat TM and MSS data, coverage and characteristics

TM Band	Band width (um)	Waveband colour	Examples of principal characteristics
1	0.45-0.52	blue	Good water penetration, strong vegetation absorbance.
2	0.52-0.60	green	Strong vegetation reflectance.
3	0.63-0.69	red	Very strong vegetation absorbance.
4	0.76-0.90	near infra red	High land/water contrast, very strong vegetation reflectance.

5	1.55-1-75	middle infra red	Very moisture sensitive.
6	10.4-12.5	thermal infra red	Very sensitive to soil moisture and vegetation
7	2.08-2.35	middle infra red	Good geological discrimination.
MSS Band			
1	0.5-0.6	green	Strong vegetation reflectance
2	0.6-0.7	red	Very strong vegetation reflectance
3	0.7-0.8	near infrared	Very strong vegetation absorbance
4	0.8-1.0	near infrared	High land/water contrast, very strong vegetation reflectance

Data compression

Principal component analysis (PCA) is a statistical data compression technique. Within a dataset, e.g. bands from a satellite image, this technique replaces the original wavebands which describe the data with new orthogonal axes that better describe the particular scene under study (Fig. 9). The principal component transformation results in a new image with new axis which are placed in the directions of high variance of the data (Simes 1992). The axis of the first principal component has the direction of maximum variance why this single component in many cases can be used instead of the original data layers. The loss of information will be small since the first axis usually contains more than 95 % of the variance in the image, provided proper selection of wavebands.

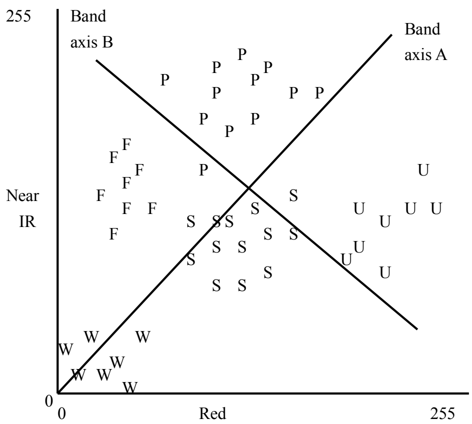

Fig. 9. Illustration of a Principal Component Analysis. New band axes are placed at the highest variance.

Colour spaces

When analysing a colour image we normally do not refer to its elements in terms of proportions of red, green and blue (RGB). Instead we tend to think in terms of hue, lightness and saturation (HLS) (Fig. 10). The colour spaces can be described as a co-ordinate system with hue, lightness and saturation on the axis in a cone. The hue of an object corresponds to the colour, and it is the average wavelength of light which the object reflects or emits. Lightness (or intensity) refers to colour brightness and is a measure of the total amount of energy involved in all wavelengths. Saturation corresponds to the colour purity and expresses the range of wavelength around the average wavelength in which most energy is carried (Bonham-Carter, 1994).

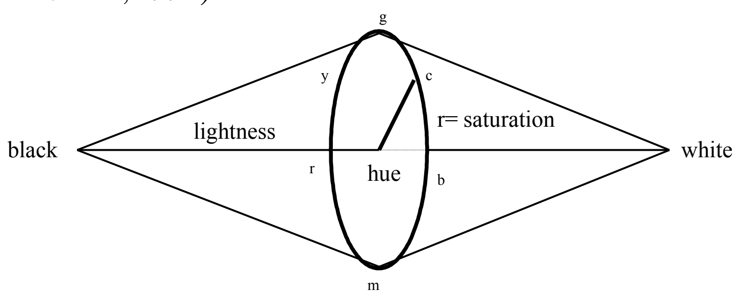

Fig. 10. The colour spaces illustrated as a cone. The intensity (lightness) axis ranges from black to white. Hue is the angle around the intensity axis in the colour circle covering blue (b), magenta (m), red (r), yellow (y), green (g), cyan (c). Saturation is the radius from the axis to the periphery.

Vegetation index

Leaf area index (LAI) is defined as the area of leaves per unit ground area. When calculating LAI two wavelength bands are needed, one with strong vegetation reflectance (Near Infra red - NIR) and one with strong vegetation absorbance (Red - R).

$$LAI = 5\text{*SAVI-0.5} \qquad \text{where} \qquad SAVI = \frac{NIR - R}{NIR + R + L} * (1 + L)$$

and L is a general estimation of the vegetation density (L = 0 for low vegetation density, L = 1 for high density) (see McCarthy, 1996). This LAI is used as input in the hydrological PHASE model, and can also be used as a band for improving supervised classification.

Digital image classification

Digital image classification methods can be divided into those based on single characteristics and those also considering their contextual positioning. Methods could also be divided into statistical and knowledge or rule based. Recent development aim at combining elements from different techniques

Supervised classification

Supervised multispectral classification is the most common method for landuse classification. In this method the analyst specifies representative training areas, i.e. samples of known land cover, which are used to calculate multispectral histograms and e.g. spectral mean values, variances and covariance. These are later used by the classifier as the rules for extrapolation of the rest of the image (Curran 1985). Examples of classifiers are minimum distance to mean, parallelepiped and maximum likelihood classifiers. Both supervised and unsupervised classification are based on individual pixel characteristics, they do not consider e.g. spectral properties of neighbours.

Unsupervised classification
Unsupervised or cluster classification does not utilise any training data. Algorithms perform a grouping procedure (clustering) on all pixels in the image and the analyst must identify the derived cluster areas afterwards. There are many different algorithms for unsupervised classification. The method used in IDRISI is based on a false colour composite. The cluster is made through a histogram peak technique and the pixel values are assigned to the nearest peak in the histogram. The division between classes falls at the midpoint between peaks. More advanced methods are available in other GIS packages.

Advanced image classification methods

Contextual classification/filtering
In high resolution images, adjacent pixels can be highly correlated. One reason for this is that land-cover of a certain type can be considerably bigger than the size of the pixel. In case of a pixel at a boundary of two cover types, its spectral response carries mixed information about these neighbouring areas and brings confusion to traditional statistical classification. The correlation of adjacent pixels is thus not constant throughout a scene. It may be very high over uniform cultivated areas or there could be no correlation in highly exploited, urbanised regions.

At the research level spatial investigations move into algorithms to process both contextual and spectral information together. A simpler approach is to apply a method similar to filtering technique, with a moving window, after the classification of pixels by any of the point-specific classifiers (Bernatek, 1995[8]).

Knowledge based classification
Expert systems are computer systems that help to solve problems which would normally require a human expert's interpretation. A knowledge based (or rule based) system is a type of expert system where knowledge is organised in three levels: facts, rules and inference. This should be compared to a conventional computer program where knowledge is organised in two levels: data and program (Robinson and Frank 1987). *Guide* can be used for a forward propagation (or chaining) classification using declarative knowledge (see appendix 6 in project instructions for Targeting critical areas for non point sources eutrophication)..

Accuracy assessment

A classification result without some measure of the classification accuracy is more or less worthless. Accuracy assessment can be done in different ways. The simplest, but also the most subjective method is visual evaluation. The classified image is compared to an existing image or with the original RGB image. A method to get an objective measurement of the accuracy is to analyse the training areas. In the ideal case, the training areas should be classified completely into the classes they were used to describe. The overall accuracy of the classified image may be evaluated by comparing the image to field observations. If the field observations have been sampled correctly, this is the most objective and correct method. It is also the most time consuming method.

Spatial allocation techniques

In a multi criteria evaluation (MCE) a suitability map is derived in the context of a specific objective. In reality however, decisions concerning landuse or environmental management usually are multi objective. Objectives may be complementary or conflicting in nature. Complementary objectives can often be solved by a hierarchical extension of the MCE technique process. For example by combining suitability index for different objectives (Voogd, 1983). Conflicts can be solved by a prioritised solution or a compromise solution. Both can be supported in GIS. Most early examples of multi-objective decision making

[8] Such a classifier for IDRISI images is avalible as *context.exe*.

relayed on linear programming solutions (e.g. Jansen and Rietveld, 1990). With many criteria to evaluate this becomes difficult, especially in spatial dimensions.

Economic theory of resource management

Economy (from the Greek words, *oikos*, house and *nomo*, the subject of) is the science that deals with management of scarce resources. Much of the debate on the economy of natural resources originated in the late 18th century. Land, labour and capital was seen as the basic resources (and constraints to production) in the economy. Still much of today's debate echo the two main views, that land is finite and we will run out of it versus that competition and innovation will continuously solve the problem through the invisible hand of the market. Land is today synonymous with natural resources, and labour is tending to be more of human resources, whereas capital is machinery, equipment etc. The acceptance of water as a limiting factor comparable to land is recent (Falkenmark, 1986). A possible explanation for this is that water in early industrialism was not a limiting factor in the North.

An alternative view is the institutional economy where group interests and environmental necessities are seen as the driving force of changes in the economy (Myrdal, 1978; Söderbaum, 1988). The most important historical driving force being population growth and the accompanying bursting of ecological carrying capacity frameworks (Wilkinson, 1972). An outgrow of this tradition is the position analysis (Söderbaum, 1988) and multi criteria evaluation (Voogd, 1983). You can find more information on the subject in standard literature in micro-economic theory (e.g. Mansfield, 1985).

Any economic system must solve four tasks. First it must allocate resources among competing uses. Secondly it must determine the level and composition of output. Third it must determine how goods and services are distributed. And finally it must provide for whatever rate of growth the society desires and can achieve (*ibid*.). Micro-economics deals with the behaviour of individual economic units like consumers, firms and resource owners. It emphasises willingness to pay and the function of the price system. Environmental problems in traditional economic theory is thus a micro-economic problem. Where the optimum level production and pollution can be estimated through the markets pricing of goods and services, also those supplied by Nature.

Water policies and pricing for a sustainable development is presently much debated, notably by the world bank (e.g. The World Bank, 1993; Serageldin, 1995, and references therein) and in Sweden by the Beijer Institute (e.g. Folke et al., 1991; Constanza et al., 1993).

Economic modelling

Traditional neo-classical economic theory starts with the assumption that both individuals and companies maximise their benefits. Goods and services are seen as desirable, and thus a market is created for them. The price is solely dependent on demand and supply, and an equilibrium is reached, which then sets the price. People with a willingness to pay equalling or exceeding the price then buys the commodity or service. In the long run the producing company will adjust to this level, and the price become dependent on the companies cost for raw material, production etc. (whether good or service). If input costs increases or decreases the company can change its pricing. The maximum benefit the company can make depends on its marginal and total costs of production, and the change in consumer demand when changing the price. The latter parameter is called price elasticity, and is of importance for the company price policy.

Major critique against the neo-classical theory is that it assumes a perfect (friction less) market place. With each competitor having equal information and access to products and services offered. Earlier the pricing of certain natural resources were seen as zero, *inter alia* air and water. The influence of environmental pollution was disregarded until the famous article by Coase (1960) - the so called coase theorem. He argued that environmental pollution caused social (or common) cost. The cost was too small for each individual to defend, but the total cost was large. Thus the economy caused *external effects*. In another, equally famous article, G. Hardin (1968) argued for “the tragedy of the commons“: the fact that for many economic activities a single person will benefit marginally from increasing his consumption but at the same time decreasing the total consumption (i.e. welfare or system sustainability). Much of the discussion in e.g. Agenda 21 is on how to *internalise* external costs to the producers. (Note that you can also have positive external effects, e.g. from your neighbours’ nice garden). The water cycle, irrigation could be seen as a positive external cost, whereas polluting water, consumption and withdrawing water from its terrestrial looping could be seen as a negative external effect. A way to mitigate those effects would be to subsidise socially beneficial use and put fees on damaging use. If this could be done in a perfect market, this policy would be enough for reaching a perfect allocation of water use. The division among the users would then depend on their willingness to pay and the price elasticity. Remember that MCE itself grew out of a critique against the neo-classic theory and is hence an alternative way of regarding the problem of scarce resource allocation.

Study site: Cyprus

Cyprus, the third biggest islands in the Mediterranean sea, has become a place where a lot of tourists spend their holidays. Cyprus major GNP generator is agriculture, and since this eastern part of the Mediterranean is dry, extensive irrigation is needed. Together with population growth this means that Cyprus today faces water stress (Engelman and LeRoy, 1993). And the prognosis is that Cyprus by the year 2025 will face water scarcity. Nota bene: water stress is defined as less than 1 700 cubic meter per person and year, water scarcity as less than 1 000 cubic meter per year.

Naturally, most of the tourist resorts are situated by the sea, and so are also most of the Cypriot cities, with Nicosia, the capital being a major exception as it is situated at the Central Plain. Villages however are scattered all over the island. There is a constant construction of new hotels going on in the towns and villages, and since there also is a need for residential buildings the tourism may give rise not only to conflicts regarding water management, but also to conflicts concerning the town planning. There is a lack of productive soils on Cyprus, and the construction of hotels also affects the agriculture since fertile land sometimes is used for hotel sites instead of agriculture. Also the growing industries compete for land and water.

Average annual water balance for Cyprus 1939-1989 is depicted in Fig. 11 (Water Development Department, 1989). Total dam capacity in Cyprus is today approximately 300 million cubic meters. Per capita consumption of water in Cyprus is approximately 150-250 litres per day. The total annual consumption in Limassol is 10 million cubic meters (200 litre person and day), and in Larnaca 4 million cubic meter per year (150 litre per person and day). Total area under irrigation is approximately 30 000 hectares. Even if the total amount of water on Cyprus would be enough, a spatially concentrated increase in use might still not be possible. Also remember that approximately 37 % of the island is inaccessible (occupied by Turkey since 1974). However, just as a parenthesis, Nicosia is supplied by water from that side. Also it will be difficult to distribute water from one side of Troodos to the other. Some more information on the water balance in Cyprus can be found in appendix 2.

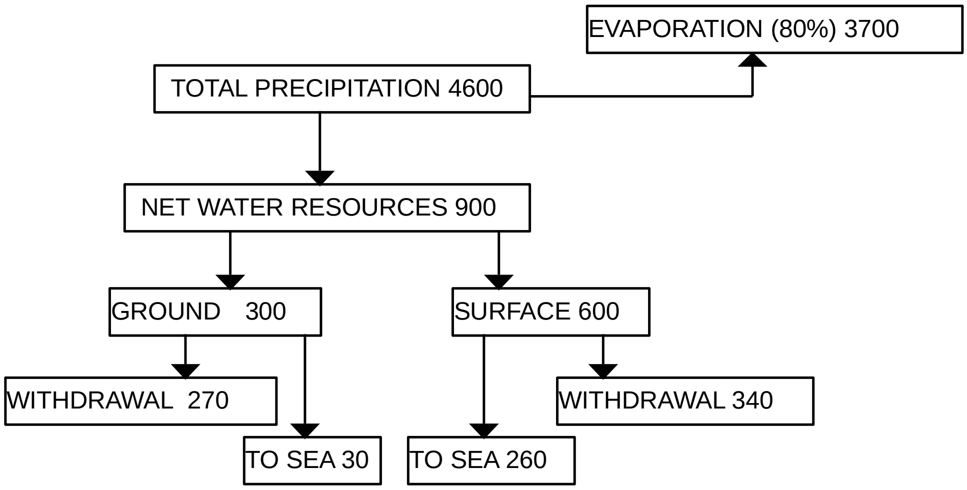

Fig 11. Water cycle for Cyprus, annual average for the period 1939-1989. Figures expressed in million cubic meters per year.

Study site: The Managua aquifer, Nicaragua

The capital of Nicaragua, Managua, is situated next to a large aquifer, which is used for its water supply. The city of Managua is rapidly expanding and this threatens both the quantity and quality of the Managua aquifer. The quantity problem has led to overexploitation of ground water in the vicinity of the city, and led to quality problems because of induced infiltration from the nearby, and strongly polluted, lake Managua. This problem is now managed by seeking new well sites in the aquifer localised further away from the city. It is however not clear how large reacharge areas are needed for the future water supply (table 2).

Table 2 Prognosis of water demand in the Managua area

Apart from being connected to the overexpoitation, the quality is also threatened by different activities related to the expanding city. Activities including intensified agriculture, non-point sources of metals from e.g. illegal dumping sites. Petro-chemical products are increasingly entering the area, refineries are established, as are gas-stations. The road system and its traffic is also growing steadiliy.

Study site: Kristianstad plain

The Kristianstad plain holds Sweden’s largest aquifer. The aquifer is used for the regional water supply and irrigation. The main aquifer is the sand stone (Glauconit), but also its overburden (both coarse soils and limestone) holds large volumes of water. The regional balance for the Glauconite aquifer has been estimated as follows (Gustafsson et al., 1988):

recharge:	3.2 m^3/s
withdrawal (wells)	0.5 m^3/s
discharge (to land)	2.0 m^3/s
discharge (to sea)	0.7 m^3/s

Ground water withdrawal for the Kristianstad plain is summarised in table 1 (*ibid*.)

Table 1 Groundwater withdrawal in million cubic meters per year from the Kristianstad plain.

Year	1969	1978	1986	2000
Municipal	4.8	7.5	8.2	8-9
Industrial	5.6	4	4	4-5
Irrigation	0.5	5-6	8	10 (17)*
Energy	-	-	0.3	1
Total	**10.9**	**16.5-17.5**	**20.5**	**23-25 (30-32)***

*Maximum during dry years

Gustafsson et al. (1988) in their review on ground water investigation of the Kristianstad plain concluded that ground water withdrawal has not affected the water volumes in the aquifer. Fluctuation in groundwater levels are attributed climate conditions, except for in the Fjälkinge region where the Glauconite is thin and withdrawal for irrigation is high during dry summer periods. A ten year time series of precipitation pattern and groundwater levels can be found in appendix 3 (measurement points are shown in the image *grw*). Due to the intense agricultural activity levels of nitrate are high to very high in the upper soil layers. However, so far nitrate levels in the Glauconite has only been rising in some recharge areas. At Nävlingeåsen and Linderrödsåsen, nitrate levels of 30-50 mg NO_3 per litre have been reported.

Water recharge and water quality of the aquifer is related to the activities at the earth-atmosphere interface. Human alteration in land use will have effects on the aquifer. By changing the land use pattern the hydrological cycle will be changed. and potentially the introduction of pesticides, fertilisers etc. could have negative influence on the water quality. Another threat is the expansion of the city of Kristianstad, and new municipal waste localisation for the city. The urban expansion, the agricultural demand for benefit and need to protect the aquifer are competing objectives, all demanding land areas.

Objective

The objective of this project is to develop an integrated management of landscape site (structure) and flow (process) resources. You can choose to this from different perspectives based on your interests.

Landscape patterning by digital data (compulsary for **Nicaragua**, sub task for **Cyprus**)
Create a land use/cover image using digital image classification methods for **Cyprus** or the **Managua** aquifer, and evaluate the accuracy (it is good to test several methods - e.g. expert system versus traditional supervised classification). If you choose not to do image classification, but still want to work with the **Cyprus** problem you will receive a classified image from us. In this case you must either study hydrological and/or economical modelling in more detail (i.e. do one subtask as compulsory).

Mapping of groundwater pollution potential (compulsary for **Managua**)
From the existing maps a DRASTIC index of groundwater vulnerability shall be constructed.

Multi objective land allocation (**all sites**)
Based on the land use/cover map and digital images of geology and elevation etc (available for **all sites**). you shall then use multi criteria evaluation to identify suitable areas for different activity. As these activities potentially use the same sites, you should find either a compromise or prioritised solution for allocation.

Linking patterns and processes (compulsary for **Cyprus** and **Kristianstad**, subtask for **Managua**)
As the land use/cover change will bring about changes in the hydrological cycle you should evaluate the impact of the water resources of the change in landscape pattern brought about by your allocation in land use/cover (**all sites**). The potential risk for ground water pollution following allocation of different activities shall be evaluated (**Kristianstad** and **Managua**).

Optional subjects include evaluating the economic feasibility of increased land and water consumption among the different conflicting water users. The demand curves for land and water is probably different for tourism, industry, agriculture and residential use. The costs for distributing water is also dependent on the aggregation of users and the distance from sources (dams/wells). You can use this knowledge to infer economic incentives for changes in land and water allocation to compare with your main scenario. An alternative is to study different economic approaches for resource management, *inter alia* neo-classic economic theory versus institutional economic theory. You can also choose to use an additional method for land use/cover classification in combination with contextual classification using the program *context*. A subtask is to penetrate the hydrological modelling and try to create better scenarios for the future water resources. A major problem on **all sites** is erosion and the loss of forests that has occurred. A subtask is then to identity suitable areas for reforestation. For this you can use MCE-technique, rule-based search or multispectral classification (cf. Gumbricht et al., 1995b[9]).

The Cyrpus study is more directed towards surface water problems and arid climate, whereas the Kristianstad plain and Nicaragua studies deal with groundwater problems in temperate and arid climate respectively. The different sites also reflect countries with large differences in economic development. The Managua study is better suited for students from Sustainable infrastructure.

Tasks

[9]Can be found under G:\KURSER\AOM\1B1636\NRM\ARTICLES \Ecoeng.doc

For **Cyprus** and **Managua** land cover maps are needed. For **Cyprus** you can either chose to do this yourselves, or have it from us. In the latter case you must do one sub task as obligatory. If you choose the **Kristianstad** study you will have a land cover map directly.

Use the land use/cover map from your chosen site, together with geology, elevation etc., for allocating sites for new land use. In Cyprus land should be allocated for tourism, agriculture, residential areas and industry, in a compromise solution. In the allocation you should not only consider scarce land resources, but also scarce water resources. In the Kristianstad plain land shall be allocated for new well sites, new solid waste disposal site, urban expansion and agriculture, probably using a prioritised solution including buffer zones for water protection is needed. For the **Managua** aquifer you should first create a map of groundwater pollution potential (i.e. a DRASTIC index). Then you should allocate sites for new wells, urban expansion and agricultural development.

As the land allocation will change the water resources dynamically you must model the hydrological condition iteratively based on your scenarios (sub-task for the **Managua** aquifer).

In Appendix 1 you find some help for how to go ahead in front of the computer.

Optional sub tasks

In order to receive a higher grade you can choose to do one of the following sub tasks:

- Improve your image classification by trying out different pixelwise methods. You must use a contextual approach to try to improve at least one of the classification results. You can also evaluate the uncertainty in your land use/cover image and include it in the MCE´s to see how it changes your land allocation.

-Identify suitable areas for reforestation (**all sites**). For this you can use MCE-technique, a rule-based search approach or multispectral classification. Evaluate the change in the water cycle potentially brought about by the reforestation. How could the changes influence selection of favourable sites?

- Include a micro economics analysis in your allocation of future land use/cover. You can do this either by assigning a willingness to pay for different criteria and the four conflicting objectives. A more interesting approach is to create a demand curve for water for each objective, and include the cost for water transport (from the dams/wells) in the pricing of water, and then see if you can find a new allocation. You are also welcome to study the economics of the scarcity in land and water resources from a theoretical viewpoint, referring to the conditions at your site.

- Study the literature on policy, pricing and management of water resources (e.g. from the World Bank) and relate the ideas to the project approach and its results.

- Develop a regional ground water balance and flow model for the Kristianstad plain that can be used for evaluating the pumping tests that you are going to do in quantitative hydrogeology.

- Develop a scheme for protection of water quality of the aquifers in the Kristianstad plain.

- Do a water balance study with the PHASE model for the Managua aquifer.

The project must be reported in a written paper. Your sub task should be presented as an interwoven part in the paper. Use times roman, size 12, with double spacing and margins on all sides of 2.5 cm. The paper should contain the following:

Title

Abstract	
Key words	
Introduction	Why did you start?
Material and methods	How did you do it?
Results	What answer did you get?
Discussion	What does it mean?
References	Written as in this instruction!

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Appendix 1

Some help in front of the computer

Start the project by login, go to G:\KURSER\AOM\1B1636 and write *cyprus_p*, *kristi-p*, or *nica_p* to start a batch program that will create a directoriy (H:\cyprus, H:\kristian or H:\nica) with the necessary files. If you repeat this commando later you can loose all the information you have created.

To use the *color85* module in IDRISI, activate the graphics driver 8514/A by the command *rixai8*. The Cyprus images are in a resolution of 300 meter, the Kristianstad images have a resolution of 50 meter, and the resolution for the images over the Managua aquifer is 100 m. Start by having a look at available images (*list*).

Vegetation mapping (all sites)

For all sites you need vegetation maps for different purposes (see below). Thus you can start by creating a map of leaf area index (LAI) (see the formula above) for you selected site. You can do the LAI by using *overlay* and *scalar.* For the Managua project there is a batch file called <lai84.bat>. Look at the bat file in any editor (e.g. **edit** in IDRISI*)*, and complete it by changing “?” into numerical values.

Landuse classification (Cyprus and Managua)

A landuse map is needed for identifying and allocating new land uses and for modelling the water cycle and changes in it after re-allocation of land. You can create the map by unsupervised classification, supervised (statistical) classification or rule based classification. The classification should be done according to the categories in table 1:1. All classification methods require iterative improvements in different steps for reaching satisfying results. Some predefined training areas you can find in your directory (vector files with names corresponding to the classes in table 1:1). A large problem in **Cyprus** is to identify towns and villages. Thus you find some towns in the image <town> already identified.

Table 1:1 Landuse categories to identify in Cyprus

Landuse	Training data files
1=Water	*water*
2=Saltlake	*saltlake*
3=Vine	*vine*
4=Agriculture	*agricult*
5=Forest	*forest*
6=Barren land	*bare*
7=Garrique/maquis	*garmaq*
8=Orchards	*orchard*
9=Built up areas	*builtup*

Table 1:2 Landuse categories to identify in Managua

Landuse	Training data files
1 = Water	*Laguna*
2 = Agriculture	*Agricult* / *Yearcrop* (annual crops)/ *Grazing* (extensive) /*Cofftree* (coffee and trees) / *Citrus*
3 = Forest/bush land	*Forest* / *For_bush* (forest and bushes)/ *Bushes*
4 = Barren land (lava fields)	*Lava*
5 = Built up areas	*Builtup*

One very important thing to note is that you must classify land use in exaxtly the suggested categories, and the sequence given. Else the accuracy control will not work.

A good strategy is to start with either supervised or unsupervised classification, evaluate the accuracy, and use this classification and its result as input in an improved knowledge based classification. Such initial accuracy contols are prefarably done against the training data (which must be rasterized first).

Unsupervised classification

Create a false colour composite with *composite*. The contrast stretch type should be linear with saturation. Have a look at it in *color85*, and see if you can distinguish the classes you want to identify. You can do this by using *v* and superimpose the training fields over the composite image. The composite image could then be used in *cluster* which provides an unsupervised classification. As the number of classes in the final map are nine, choose some more classes. The best thing to do is then to use *errmat* and check the cluster result against some ground truth image - suggestively reasterized traing areas. By this approach you will see to what landuse class the different clusters belong. Then use reclass to create a landuse image from the cluster image.

Supervised classification

In the multispectral classification method, the reflectance properties are considered and there is no need for ancillary digital data. However, it might be useful in an area with diverse geology that highly influences the spectral reflectance. Thus you can base the classification on just satellite data, ancillary data, or a combination thereof.

For each of the classes stated in table 1:1 / table 1:2 you must find training areas (which are mostly predefiend by us for the project). The selection of training areas is the most important step in a supervised classification. The objective of training is to obtain a set of statistics that describe the spectral response pattern for each category to be classified. The statistics are used to determine decision rules for the classification of each pixel in the whole image data set. Two things are important in selecting training areas. First, the training data for each class must be representative of all data for that class, and second, the training data for each class must come close to fitting the distribution assumption on which the decision rules are based. (Maximum likelihood statistics are based on probability and requires normally distributed data.)

Representativity means that training statistics must be obtained for all spectral classes for each category to be classified. If your image contains two types of agricultural soils, you must use separate training areas for the two subclasses. These training areas should be used to create separate signature files and thus be separately classified. You can merge them together as a final step in the production of a thematic map, but only then.

Display an image (preferably the colour composite) and identify homogenous areas to be used as training areas. Digitise them as areas and carefully note the id and the class it represents (according to table 1:1 / 1:2). Note the possibility in IDRISI to have more than one training area for each class that you want to identify.

From the information in the training areas, multispectral signatures are created with *makesig*. Give logical names to the classes. Each class will now be accompanied by a signature file containing statistics (*.sig) and a signature pixel file (*.spg) with the rasterised data. Look at the separability of your classes in *sigcomp*. To improve the separability, you can create new training areas, or you can manipulate the signature statistics file (*.sig) directly. Manipulation means that you can change information based on some empirical or hypothetical ground. The module *editsig* are used to edit the signature files.

There are several algorithms available for doing the classification from signature files in IDRISI; *maxlik, mindist* or *piped*. Choose the method you find appropriate (maximum likelihood, minimum distance to means classification or parallelepiped classification). One way to improve your supervised classification is to first create a vegetation image or a PCA and use it as a complementary band.

Rule based classification

In a knowledge based classification, rules that determines the outcome are set by the user. You can use *guide* as an inference tool in the classification. Guide outputs a raster map layer where the category values represent the application of the user specified criteria (see instruction on targeting critical areas for non point source eutrophication). In the rule based classification, you should use several different data layers. Some of them you need to create yourself. In table 1:2 you find some suggestions of data layers suitable for the analysis.

Table 1:2 Data layers suggested for rule based classification

Principal component analysis, PCA
Lightness
LAI (Leaf Area Index)
False colour composite cluster (unsupervised classification)
Geology
Elevation
Slope
Aspect

Run the module *pca* to create the principal component layer from a satellite image with several bands. If the first component carries a significant amount of information you can use it in the classification.

The three Landsat TM bands could further be used to create a lightness component. The conversion between RGB (red, green, blue) and HLS (hue, lightness, saturation) is done by *colspace*.

Due to the arid climate of Cyprus, the Leaf area Index (LAI) must be derived from images recorded in springtime when the vegetation still have vigour. Thus, the Landsat MSS scene from April, 1987 should preferably be used.

From the digital terrain model, create images for slope and aspect with the module *surface*.

When the data layers are completed, your next step is to define training areas from which you extract information for the guide programme. Extract knowledge from the training areas (given in table 1:1 / 1:2) by using *pinguide,* and execute the expert rules using *guide*. *Pinguide* can be parametized by a text file, and the file <pin.pin> in your directory will do it for you, given that your image files have corresponding names (look at <pin.pin> with the editor to see). Try to improve the result by manipulating the guide-file rules, or by changing training data set.

To improve your classification, iteratively change the figures in the file. Change the thresholds if there are many unclassified pixels or if your accuracy level is too low. Compare the result from the alternative classification method and choose the best map as input for further analyses.

Accuracy assessment

The accuracy of the classified image is determined by comparing the image by a set of ground truth data. Use *errmat* or *crosstab* to execute the accuracy evaluation. To get the result as a file, set output under *envrion* to log. The ground truth data for **Cyprus** and **Managua** will be available at the end of the project. The accuracy assessments are presented in a matrix form where the columns correspond to the classes in the classified image and the rows to the field data points or training areas. In each cell the number of pixels having this particular combination is given. In a good classification, the high values should be concentrated along the diagonal of the matrix.

Mapping groundwater pollution potential (Managua)

In your directory you have all the necessary input files for creating a DRASTIC vulnerability index (table 2). Except precipitiation. The vector file "prec" contains point information on average annual precipitation. We have also made a guess about precipitation in the map corners in the file. Use <prec> to create a precipitation image over the whole recharge area. You can either use **interpol** or **thiessen** (directly on the vector file). Read carefully in the IDRISI manual, and use your hydrological knowledge to decide on which method to use. Look at your result with the help of **color**. Then it is time to create all the layers needed for the DRASTIC index (see appendix 4).

Table 1:2 Creation of DRASTIC layers

DRASTIC layer	Created by
depth	*overlay* ("DEM"- "phreatic").
recharge	*updrain* on <DEM>*, reclass* of "land cover classification" and "LAI", and *overlay* with "precipataion".
(aquifer) *media*	*reclass* of "geology" (complete the file "media.rcl").
soil	*reclass* of "soil" (complete the file "soil.rcl").
Impact of vadoze zone	*guide* applied to soil and media
topo	*surface* and the "DEM", and then *reclass.*
cond	"Transmissivity" / ("*phreatic*"-"*imptop*")

Comments to table 1:2

Recharge is dependent on primarily on precipitation, and the amount of water flowing. You should have created the precipitation image above. The amount of water flowing passed a given pixle can, in a simplified approach, be estimated from the updrain area. We have created such an image for you called <updrain>. It was created by the programs under P:\DOS\IDRISI\UPDRAIN, and you are welcome to try the different algorithms available (the program must run under windows environment). Of the amount of water entering a cell, a part will be evapotranspirated, some will run off, and only a part will lead to groundwater recharge. The evapotranspiration and run off is dependent on vegetation cover (i.e. LAI) and slope. Thus you must use these factors as input. The easiest thing to do is to complete the file <recharge.bat>, and give appropriate figures for the functions of evapotranspiration and run off.

Conductivity can be calculated as transmissivity divided by aquifer thickness. The aquifer thickness can be calculated as "ground water table" - "top of impermeable layer" using *overlay*. You can **edit** the file <cond.bat> to execute those calculations.

When you have created all the DRASTIC input images you will get the index by completing and executing <drastic.bat>.

Land shortage

<u>*Cyprus*</u>

As Cyprus economy is prospering there is a conflict over land use since suitable land is becoming scarce. Major future land users are tourism, residential settlements, agriculture and industry. Land suitability for those user categories is differing from some perspectives and conflicting from others.

Before continuing you must decide how much land you want to allocate for the different objectives. When doing so you must take a glance at the available water resources and the consumption of water in industry, residential areas, tourist areas and agriculture respectively. The development prognosis says that population will go up with 10 000 persons per year, and that tourism will increase equally much in number of beds needed. Assume that you can host 25 to 50 persons per hectare in urban areas. Each person consumes approximately 150 - 250 litres of water per day. Agricultural development should be able to supply food for the increase in population and tourism with foods. The demand for irrigated land is a hectare for approximately 5 to 10 persons. And then it needs irrigation with 200 to 300 mm water per year. Based on those figures you can estimate the need for both land and water. Industrial needs and uses must also be estimated. Note the potential solution of reusing water at least from residential and tourism use for agriculture.

<u>*Managua*</u>

Managua is rapidly expanding, and this expansion can only be towards the aquifer. Thus it is important to secure land for future well sites as well as protecting the aquifer. The water supply should be prioritized over the urban expansion.

<u>*Kristianstad*</u>

Scania is a prospering region in Sweden, thus demand for land is high. The city of Kristianstad need areas for expansion. The expansion also mean demand for more water, and thus new sites for water production wells. The expansion means more waste production, and the city is presently searching for new sites for waste disposal. These three land uses compete with each other and with mainly agricultural interests for land. The objectives are competitive in character, and probably a prioritised solution must be sought.

<u>*GIS tools for spatial allocation*</u>

Multi criteria evaluation (MCE) and multi objective land allocation (MOLA) are decision support tools incorporated in IDRISI that can be used to solve spatially related problems. The first thing to do is to do a multi criteria evaluation for each of the conflicting objectives. Start by listing constraint and factors to include in the decision rules for finding suitable areas for the four future land uses. Obvious areas to constraint include water and built-up areas. You can also restrict the analysis to a certain geographic region. Factors are strongly varying, but you can have some hints by the MCE project on ecological villages. To compare the relative importance of the factors, construct a pairwise comparison matrix. The relative importance should be given values from 1/9 to 9/1 (Fig. 1.1).

	landuse	roads	centre	beach
landuse	1			
roads	3/1	1		
centre	7/1	2/1	1	
beach	1/5	1/4	6/1	1

Fig 1:1 Example of matrix for relative importance of pairwise factors.

After having discussed the relative importance, use *edit* in IDRISI to create a pairwise comparison file (option 6). Using the data from Fig 1:1 the file should look like this:

```
4
landuse
roads
centre
beach
1
3 1
7 2 1
1/5 1/4 6 1
```

The first line indicate number of factors, the rest is fairly obvious. Once the file is created, run *weight*. You will be presented with best fit weights and a judgement of the consistency of the weights. Repeat the pairwise weighing iteratively until you get a consistent set of weights. Note those weights. Run *mce* for the four objectives agriculture, industry, tourism and residential areas.

In the suitability index maps, you will probably find that different objectives have high score areas at the same location. A prioritised or compromise solution is thus necessary. This can be done by the *rank* (prioritised) or the *mola* (compromise) modules, comparing the suitability maps from the mce to each other. First, give weights to the different objectives according to their relative importance. Then rank the cells in the suitability maps with *rank*. Choose an image to be used as a key for the ranking of ties (an image that you expect will have a conflicting area interest with the first). This is necessary to separate cells with identical values. The first image should be in descending (extending down) order and the second in ascending (proceeding upwards, rising) order. Decide on what area requirements to be given to the objectives.

Water shortage (compulsary for Cyprus and Kristianstad, subtask for Managua)

Before starting the hydrological modelling, run the batch file kphase_p.bat, cphase_p.bat, or nphase_p which will create the directory H:\KRISTIAN\PHASE, H:\CYPRUS\PHASE or H:\NICA\PHASE respectively, with all the necessary files for model calibration. More information on phase can be found in Gumbricht (1996[10]) and Hessling (1995).

The spatial distribution of your land use will affect the water cycle. For modelling the water resource situation there is a model - PHASE. The model is based on IDRISI and you can run it for any defined area. We suggest that you define the tract of land that act as recgharge area by on screen digitising on the *dtm* image. With a good digital elevation model the delimitation of a watershed can be done with the command *watrshed*. If you want to try it you probably need to digitise a spot or area into which the drainage area should be drained. Create a Boolean (i.e. constraint) image just identifying the identified area.

PHASE requires time series of precipitation (P) and temperature (T) , and if it should be calibrated or validated also runoff (Q) (or groundwater level for) for the identified tract is needed. Model time step can be either day, week or month. The data should be put in a text file with three columns (P, T, Q). For **Kristianstad** there is one such file (PTQ.dat), and for **Cyprus** and **Managua** there are four (PTQ(n).dat). The model parameter setting must be given in another file, which is labelled *initial.dat* in your directories. Look in that file in your directory, it explains the figures that should be given.

Compared to most other models an important parameter in PHASE is the canopy-soil-atmosphere interface. Evapotranspiration and site storage of water is partly parameterised dependent on LAI. This means that changes in land cover also infer changes in the natural hydrological cycle. The fractal internalisation of evapotranspirated-precipitated water over different land cover categories can also be parameterised by NDVI, given in *initial.dat*.

The model calculates flow from precipitation and temperature and model result can be displayed as a vector after the model run. Model output (flow and groundwater recharge in m3/s) can be found in files called *pq.vec* and *grwq.vec* respectively. The measured flow is in a file called *trueq.vec*, and the file *accdiff.vec* shows accumulated difference between model values and measurements. If you want to save a model output you should rename it (and its accompanying *.dvc* file). When the program comes to end (if it does not crash!) it ends as a displayed idrisi image. You can display your flow files as vectors in this image (use *v* and give the name), flow and time you can see by moving the mouse around. When you exit the first image another is displayed. In this second image you can display the changes in site storage of water, runoff and storm runoff, evaporation, transpiration, snow accumulation and ground water formation (all in mm per time step). The vector files containing the data are called:

mmstore.vec (mm water storage in the landscape)
mmq.vec (mm runoff from the landscape)
mmstorm.vec (mm storm flow runoff from the landscape)
mmevapo.vec (mm evaporation from the landscape)

[10] Can be found under G:\KURSER\AOM\1B1636\NRM\ARTICLES \phase.doc

mmtrans.vec (mm transpiration from the landscape)
mmsnow.vec (mm snow accumulated in the landscape)
mmgrw.vec (mm ground water formation)
prec.vec (mm precipitation)
temp.vec (temperature as from the ”PTQ” file)

There is also a text file with total runoff volume per day, month and year created after each model run. It is called *qvol.dat*.

After you have calibrated your model you can use it for forecasting or for comparing it with a scenario of changes in land use. In the latter scenario mode the alternative scenario data will be in files with the same names as above, but with an *s* as prefix.

Start by running the model for the predefined watershed(s) <*wshed(n)*>, from which the data in *PTQ(n).dat* is collected. Check the result against *trueq(n)*. Make some changes in *initial.dat* and see what happens. For **Cyprus** and **Managua** you can now transfer the model parameter setting to another watershed, and see if it performs robust. When the results are satisfying identify the watershed you want to work with. Assume that P and T for the predefined watershed and your own are equivalent, and use PHASE for generating a runoff curve for your basin. Save the results. Evaluate the changes brought about in the water cycle in your basin by running PHASE for a land surface with your new land allocation. For doing this you must assume new values of LAI for agriculture, industry, residential and tourist areas respectively. The best estimate you will get by *extract*ing values from your classified land use image.

Appendix 2 **(from: Cyprus Water Development Department, 1989)**

Appendix 3 **(from: Gustafsson et al., 1988)**

Appendix 4 **DRASTIC**