Application of Remote Sensing and Geographic Information System in Hydrological Modelling

Z. Su, P. Neumann, W. Fett, A. Schumann & G.A. Schultz

Institute of Hydrology, Water Management and Environemntal Engineering
Ruhr University Bochum, P.O. Box 10 21 48, D-4630 Bochum 1, Germany

ABSTRACT

Remote Sensing Techniques and raster geographic information system functions are developed and applied for estimating parameters for distributed hydrological modelling. The methodology of integrating remote sensing into GIS is presented. Two cases studies are included.

Key words: Remote Sensing, Geographic Information System (GIS), Hydrological Modelling

INTRODUCTION

Remote sensing techniques abd raster geographic information system functions are developed and applied at the Institute for Hydrology, Water Resources and Environmental Engineering, Ruhr University Bochum, to generate the input data for physically based hydrological models. Distributed hydrological modelling demands spatially distributed characteristics and parameters of the catchment. These data are effectively provided by integrating remote sensing products into GIS. The vast data acquisition tasks are fulfilled by integrating multispectral, multitemporal satellite imagery, such as Landsat TM, SPOT panchromatic and SPOT multispectral scenes, digital elevation data, digitized thematic maps, e.g. soil maps, amd line data into the GIS. Along with two cases studies the data structure, techniques for extracting information from digital elevation model, data acquisition, analysis, classification, data transformation (vector to raster and ratser to vector), resampling and integrating of remote sensing data will be discussed.

1. THE GEOGRAPHIC INFORMATION SYSTEM (GIS)

The term "Geographic Information Systems" refers broadly to methods for handling information which has a locational or geographic reference.

For the estimation of model parameters from high resolution data of catchment characteristics, it was necessary to set up a regional Geographic Information System (GIS) based on the ideea that the data should be referenced in a way which will allow retrieval, analysis and display on spatial criteria as required.

a) Components of the GIS

The configuration of the GIS is a combination of management subsystem, a computer hardware subsystem and a computer software subsystem (Burrough, 1986) which consists of such modules as data input and verification, data storage and database management, data output and presentation, visualized data processing and data analysis (VDP & VDA) and interaction with the user.

Data input: the data are acquired from field observations, satellite sensors and existing maps via interactive terminals, digitizers, text files, scanner and magnetic media. Verification is immediately performed in order to identify the applicability of the data and to remove primary errors.

Data storage and database management: the data are stored and managed with reference to their geographic position with a predefined regional coordinate system or reference basis (e.g. Latitude and Longitude, Universal Transverse Mercator, etc.)

Data output and presentation: data output and presentation are in the form of visual displays, prints, plots as well as magnetic media (ASCII files on diskettes, harddisks and tapes).

Visualized data processing and data analysis (VDP & VDA): Visualized data processing and data analysis thus enable the maintenance of data matching, updating, analysing and manipulating in order to extract desired information (e.g. catchment physiographic characteristics and hydrological parameters, etc.).

Interaction with the user: the designed GIS enables the user to have a direct contact with the computer. So the user is always informed about what is going on with the aid of interactive operation.

b) The Data Structure of the GIS
The data structure is built with an "overlay" concept, i.e. the real world is portrayed by a series of overlays in each of which one aspect of reality has been recorded (Burrough 1986), e.g. topography by Digital Elevation Model (DEM), landuse by classified satellite data, soil type by digitized soil map and vegetation by Normalized Difference Vegetation Index (NDVI) and Leaf Water Content Index (LWCI) as well as Leaf Area Index (LAI), etc. The event dependent data (e.g. rainfall, temperature etc.) are also represented as time variant overlays.

2. PROCESSING OF REMOTE SENSED DATA DERIVING HYDROLOGICALLY RELEVANT PARAMETERS

The remote sensing data are preprocessed including multiimage normalization for viewing angle, atmospheric and intensity variations, image registration, congrueting and rectification. The preprocessed images are then used to generate the required products, such as landuse maps which are of high importance for parameter estimation for hydrological processes as interception, evapotranspiration, infiltration and surface runoff. Vegetation indices which can be used to characterize the type, intensity and maturity of vegetation and leaf water content indices which indicate the amount stored subsurface water available shall also be provided. The information can be interpreted to describe the response of vegetation to the supply of subsurface water.

Land Use: for land use classification the available Landsat TM data have been preprocessed and the 21 bands resulted from a tasseled cap transformation (Crist and Cicone, 1984) (kt1, kt2, kt3: kt1, representing brightness, kt2, greenness and kt3, wetness), band ratio (r1=tm2/tm1, r2=tm3/tm2, r3=tm4/tm3, r4=tm5/tm4, r5=tm6/tm5, r6=tm7/tm6, r7=tm5/tm7), the 7 original bands (tm1, tm2, tm3, tm4, tm5, tm6, tm7), normalized band ratio (ndvi=(tm4-tm3)/(tm4+tm3), lwci=(tm4-tm5) / (tm4+tm5), gwci=(tm4- tm7)/(tm4+tm7)) are examined with a divergence index (Swain, 1978) to determine the best bands combination for land use classification. The resultant 6 bands (kt1, kt2, kt3, tm4/tm3, ndvi and lwci) are used for the classification applying a supervised maximum likelihood algorithm with zero threshold. The training areas are identified with the aid of existing maps, field survey, aeral photographs and SPOT pancromatic scene. The classified scene (level II) is postprocessed with applying conditional majority decision theory and the Level II classes are merged into eight land use classes (level I), i.e. water, builtup area, conifereous forest, deciduous forest, mixed forest, crop land, pasture and bushes, according to their significance for hydrological processes, e.g. interception, surface runoff, evapotranspiration, etc.

Vegetation Index: the various types of vegetation are identified with the aid of land use classification, while the state of the vegetation maturity can be indexed by vegetation indices. The NDVI is used for this purpose, which is calculated as the ratio of the difference between radiance in the near infrared and in the red, i.e. NDVI=(NIR-RED)/(NIR+RED) (Tucker, 1979), where NIR: radiance in the Near Infrared, e.g. Landsat TM band 4, spectral range 0.76-0.90um and RED: radiance in the red e.g. Landsat TM band 3, spectral range 0.63-0.69um.

Leaf Water Content Index: the absorption by vegetation in the short wave infrared is due to absorption by water in the leaves and hence measurements in this spectral band will provide a measure of the amount of available water stored in the leaves (Hunt, 1987, cited by Finch, 1990). Vegetation having a large capacity to store water in the leaves exists only in areas with abundant water supply. The Leaf Water Content Index can be defined as LWCI=(NIR-SWIR1)/(NIR + SWIR1), where NIR: radiance in the Near Infrared, e.g. Landsat TM band 4, spectral range 0.76- 0.90um and SWIR1: radiance in the short wave infrared, e.g. Landsat TM band 5, spectral range 1.55-1.75um

Soil Water Content Index: similar to LWCI, by observing the significant spectral characterisitcs of green vegetation and those of soil at various moisture contents (e.g. Hoffer, 1978), another index can be defined as
SWCI=(NIR-SWIR2)/(NIR+SWIR2), where NIR: radiance in the Near Infrared, e.g.landsat TM band 4, spectral range 0.76-0.90um and SWIR2: radiance in the short wave infrared, e.g. Landsat TM band 7, spectral range 2.08-2.35um.

The application of NDVI, LWCI and SWCI allows interpretation of the data in terms of response of vegetation to the supply of subsurface water.

Leaf Area Index: The Leaf Area Index (LAI) is defined as the areas of leaves in a given ground area and is very important parameter in modelling interception. Usually LAI is taken from Literature which in a conventional way is based on measuring LAI in one time period (say in one year) and this is assumed to represent the average of LAIs over the whole modelling period and is used for the rest of the modelling time period. Unfortunately this is inadequate because of the hilly dynamic behaviour of the vegetation (the annual variabilities). For the purpose of simulation of the effects of land use change it is impractical, if not impossible, to measure the LAI over a very large area for a long time period (i.e.the time peiod that the effects of land use change to be specified, that it at least a few years). Therefore the estimation of LAI with the aid of multitemporal image analysis in relation to field measurements (Running, 1986 and Running, et al. 1988) is of critical importance.

3. PROCESSING OF GEOGRAPHIC DATA DERIVING HYDROLOGICALLY RELEVANT PARAMETERS

The digital elevation data obtained by means of photogrammetry are used to derive the physiographic characteristics of the catchment, these are elevation, slope and aspect, drainage network, flow length and time of concentration, etc. Soil information is maintained in the digitized soil map. Other digitized thematic data are also being acquired mainly for the purpose of comparison and reference. The time rapidly variant data are stored as string data and the locations of the observation station of these data are referenced as point data.

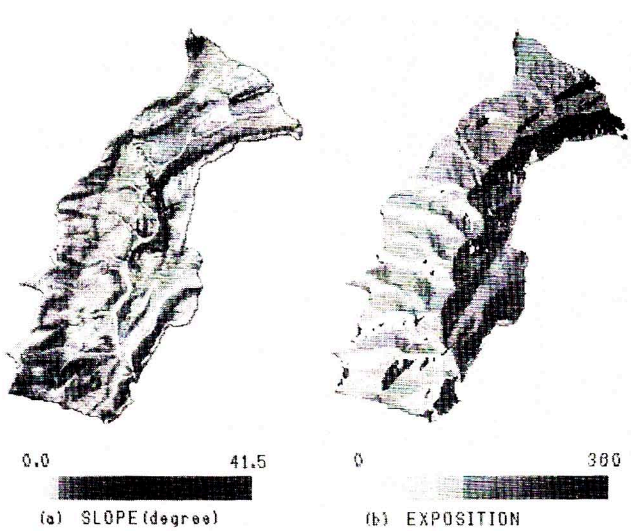

Fig. 1 - Catchment characteristics derived from a Digital Elevation Model, Nims catchment at Gauge Giesdorf (18.5 km², Mosel tributary), Germany (a) Slope; (b) Exposition (0° - 360° clockwise starting at north) (from Ott, et al., 1991).

Since a DEM is a digital discrete representation of the continuous variation of relief in space, the elevations of all grid cells form the altitude matrix. Slope is defined by a plane tangent to the surface as represented by the DEM and comprises two components namely, gradient, the maximum rate of change in altitude, i.e. the degree of slope, and exposition (aspect), the compass direction of this maximum rate of change (Marks, et al., 1984). These are derived according to an algorithm by Neumann, et al., (1990) (Fig. 1).

The algorithm used for simulating drainage networks resembles that defined by Cauchy theorem, which states that the shortest distance between any point a curved surface abd the lowest point is the line of steepest descent. Two approaches are used (The terminology follows that of Fairfield and Leymarie, 1991).

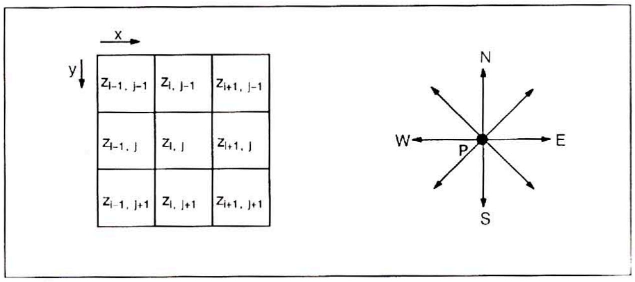

Fig. 2 - Decision neighbourhood z(q) for pixel P ($z(p) = Z_{i,j}$)

1) D8, the deterministic eight-neighbours method:
If all eight-neighbours of pixel p (Fig. 2) are at or above p's elevation, then link(p) points to p, else link(p) points to the eight-neighbour of greatest downslop, where the downslope from pixel p to neighbouring pixel q is z(p)-z(q) if p and q are slanting (corner) neighbourings. However, according to Fairfield and leymarie (1991) algorthms of this type share a fault: unless the terrain is rugged, the derived water channels tend to flow in parallel lines along prefered directions engendered by the sampling grid orientation. This problem is solved by the stochastic method Rho as proposed by Fairfield and Leymaire (1991).

2) Rho_8, the stochastic eight-neighbours method:
If all the eight-neighbours of pixel p are above p, then link (p) points to p, else link(p) points to the eight-neighbour of greatest $rhoslope_8$, where the $rhoslope_8$ from pixel p to neighbouring pixel q is z(p)-z(q9 for NESW neighbours, and rho_8*(z(p)-z(q)) for slanting (corner) neighbours, where rho_8 is a random variable taking values in the range (0.5, 1), and whose cdf is

$$P\,(rhos_8 <= x) = \begin{cases} 0, & \text{for } x < 0.5 \\ 2-1/x, & \text{for } 0.5 <= x <= 1\ . \\ 1, & \text{for } x > 1 \end{cases}$$

Let r be a uniformly distributed random variable between 0 and 1. Then the inverse of the cdf, $rho_8=1/(2-r)$, generates $rhos_8$ appropriately (Fairfield and Leymarie, 1991).

Tab.1 - Comparison of flow length from each pixel to the discharge gauge Giesdorf in Nims catchment (18.5 km^2, Mosel tributary), Germany (in 40 m)

Method	Minimum	Maximum	Average	Standard deviation
D8	.000	346.000	91.575	77.383
Rho8	.000	358.000	95.247	76.361

The flow lenght of water from each pixel to the catchment outlet (e.g. to a discharge gauge) is calculated by counting the number of links over the flow line, if the link is horizontal or vertical the lenght of this link is equal to the pixel size, otherwise it equals sprt(2) times pixel size. Tab. 1 lists the comparison of the flow length after the D8 and Rho8 method, which supplements the above argument about D8 and Rho8 method.

The time of concentration which is defined as the time it takes for waterto travel from the most distant point of a watersheld to the watersheld outlet or to some other downstream point of reference, e.g. to a discharge gauge is computed by Kirpich's formula (Kirpich, 1940). With the computed flow length of each pixel the time it takes for water to travel from each pixel to a downstream reference point can be easily calculated.

The thematic data are reclassified (regrouped) according to the properties they represent.

4. INTEGRATING REMOTE SENSING PRODUCTS INTO GIS DERIVING HYDROLOGICALLY RELEVANT PARAMETERS

The principle of integrating remote sensing products into GIS is as follows:

a) processing of the remote sensed data as discussed above to derive the required information;
b) importing the processed remote sensed products into the GIS data bank as overlays, reclassifiying and merging where necessary;
c) overlaying and intersecting these overlays with other ones to generate new overlay (overlays) containing integrated information for hydrological modelling. The general methodology is as follows:

O = f (A1, A2, A3,....An)

- where O: resultsnt object after integrating;
- A1, A2, A3, ...An: attribute of relevant overlays;
- f: function of operation to be defined, e.g. boolean operation (AND, OR, NOT, XOR), arithmetic operation or weighting operation, etc.

The technique for generating the Hydrologically Similar Units (HSUs) illustrates how this principle is implemented. A HSU is defined as a group of pixels with similar hydrologically relevant land use and soil type, equal time of concentration and lying in the same meteorological zone, within which homogeneous hydrological conditions concerning parameters, input and runoff generating processes are assumed. The mathmatical formulation of HSUs is as following (Fig. 3):

HSUs= f (L(i), S(j), T(k), P(I))

where:

f: AND operation

L(i): Land use class i, i=1, mi, mi: maximum land use classes

S(j): Soil type class j, j=1, mj, mj: maximum soil type classes

T(k): Travel time class k, k=1, mk, mk: maximum travel time classes

P(I): Precipitation zone I, I=1, ml, ml: maximum precipitation zones

4.1 Case Studies

To illustrate the principles and experiences of utilization of remote sensing data and GIS in hydrological modelling, two cases studies are presented.

a) Simulation of Rainfall-Runoff Process in the Volme River Catchment on the Basis of Grid Cells (Fett, et al., 1990)
b) Development of A Distributed Hydrological Model for Flood Forecasting and Imapct Assesment of Landuse Change in the International Mosel River Basin (Ott, et al., 1991)

The first case study presents an integrated hydrologically relevant data base for the volume river catchment in Germany which is used within a distributed hydrological model that runs on basis of grid cells (Landsat TM reso-

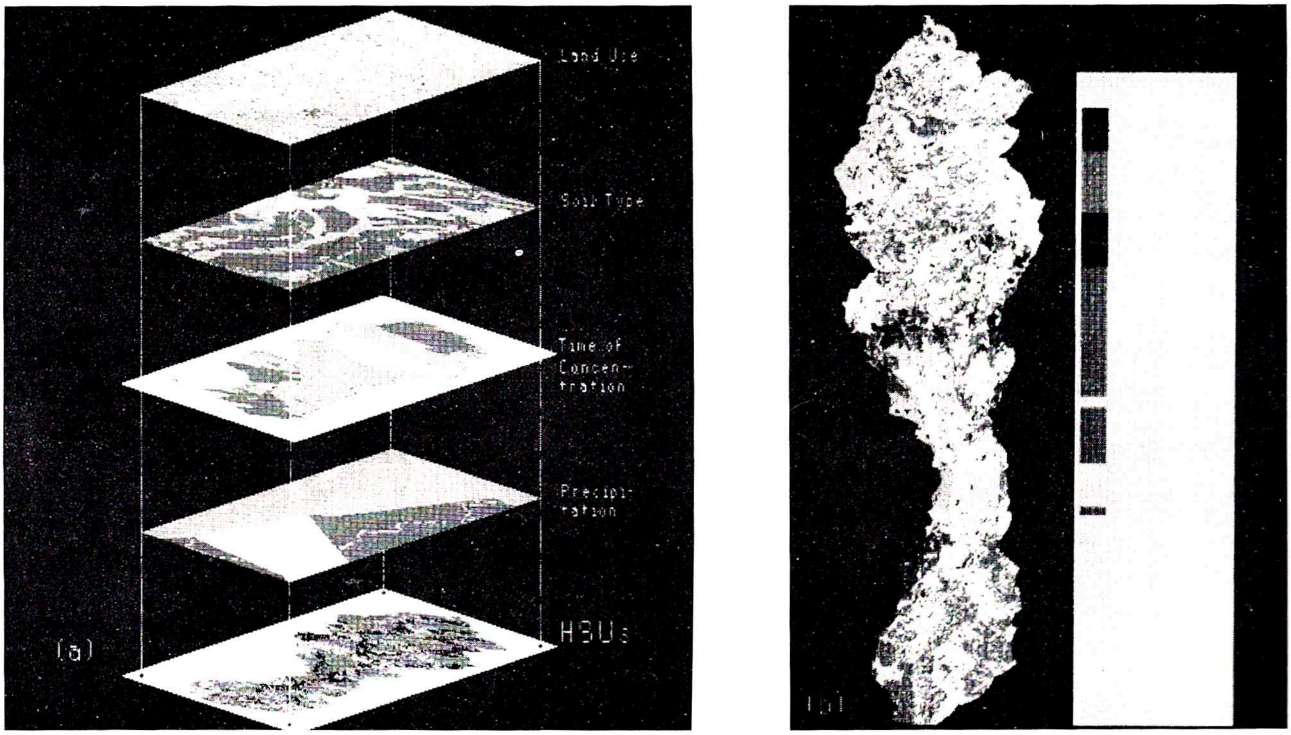

Fig. 3 - (a) The principle for generating the Hydrologically Similar Units (HSUs) and (b) the generated HSUs in Nims catchment at Gauge Alsdorf (267 km^2, Mosel tributary), Germany.

lution). The second one consists of the utilization of an "Overlay" concept in which the required informatiom, e.g. landuse, soil type, vegetation nad leaf water content indices, elevation, slope, aspect, drainage network, etc., are stored and which are used for generating the so called Hydrologically Similar Units (HSUs) by means of overlaying and reclassifying. These HSUs for the spatial basis for the distributed hydrological model designed for short term flood forecasting and long term simulation of hydrological effects of the land use and climate changes in the Mosel river catchment.

6.1) Simulation of Rainfall-Runoff Process in the Volme river Catchment on the basis of Grid Cells

6.2) Development of A Distributed Hydrological Model for Flood Forecasting and Impact Assesment of Landuse Change in the International Mosel River Basin

The research project presented has several objectives: development of a hydrological model allowing short-term and lomg- term simulation and application for real time flood forecasting, specification of the impact of landuse changes and identification of the hydrological effects of potential climatic changes in the international Mosel River basin.

Each catchment area is subdived into square area elements with a grid size of 30x30m^2, i.e. all information is stored in the format of this spatial resolution. Since such a high resolution cannot be applied to the large catchment of the Mosel RIver, a special aggregation technique had to be developed, similar to those presented by Knudsen, et al., (1986) and fortin, et al., (1990). In order to reduce computational effort grid elements having equal hydrological features are lumped together into 'hydrologically similar units' (HSUs).
to verify the performance of the model, the same parameters derived from the upper Nims catchment at gauge Giesdorf (18.5 km^2) were applied to the whole Nims catchment at gauge Alsdorf (267 km^2) with 488 HSUs (Fig. 3). It was shown (Ott, et al., 1991) that the time to peak and the peak flow as well as the dynamic behaviour of the observed hydrograph weere all well simulated by the model.

CONCLUSIONS

a) Functions of a Geographic Information System (GIS) for processing of remote sensed and digital conventional geographic referenced data for hydrological modelling are presented. Some techniques for integrating remote sensing into GIS are developed.

b) For the estimation of the model parameters in the second case study, satellite imagery, a digital elevation model as well as digitized thematic data are used. Since this type of information provides a very high resolution in space it was necessary to aggregate the small area elements into so-called 'hydrologically Similar Units (HSUs) in the geographic Information System (GIS).

c) The most difficult priblem caused by the large dimensions of the river basin was to cope with the enormous amount of data resulting from the high spatial resolution the model is based on. The application of Remote Sensing techniques and GIS is therefore essential to hydrological modelling.

d) In the long run it is intended to couple the Mosel river model with an atmospheric general circulation model (AGCM) provided by a meteorological institute. This coupling of the two models will allow the running of the model with future scenarios of a changed climate. The impact of climate changes on hydrological processes can then be analysed with the aid of the two coupled models.

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