

GIS for regionalization and visualization in hydrology

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Abstract GIS today offers a lot of multi-purpose methods for general spatial analysis but only a few GIS-tools for analysing and modelling hydrological processes. For scale invariant spatial transfers as well as up- and downscaling of hydrological information, special Tools for Hydrological Information and Modelling, "T₄HIM" has been developed, using ARC/INFO as a GIS kernel. As an example, an improved GIS-tool for aggregating flow directions in river basins is discussed. The visualization of hydrological data and processes is considered as another important research problem. "HydroVIS" couples GIS techniques with cartographic methods and multimedia approaches. The growing number of GIS applications in hydrology must not obscure our view of the conceptual and practical shortcomings of GIS. Newly developed object-oriented data models, temporal and three-dimensional approaches and the promising idea of open GIS will help to clear the path from loose coupling to full integration of GIS and hydrological models.

GIS FOR REGIONALIZATION

The application of Geographical Information Systems (GIS) to hydrological problems and water resources management has started rather late in Germany. This delay may be due to the concentration of hydrological research on the development of physically based process models for slope segments or small river basins with a high temporal but low spatial resolution. Much more important however are fundamental deficiencies of present GIS, giving very little support to hydrological modelling. The data models available in GIS are fundamentally non-dynamic, but time plays a very important role in hydrological modelling. There is an apparent lack of specific hydrological GIS-tools for spatial and spatio-temporal analyses. The integration of hydrological models and GIS fails due to the closed system architecture of almost all GIS (Maidment, 1993; Streit & Wiesmann, 1996).

Nevertheless, the interest of German hydrologists in GIS has increased considerably during the last few years, particularly in the application of digital elevation models (DEM) for automated calculation of watersheds and hydraulically effective terrain parameters. The use of remote sensing data, especially for the survey of current land use, plays an important part. Digital maps of soil and geological conditions have become more important.

Another reason for the growing interest of hydrologists in GIS is its potential to visualize spatial data. The possibility of creating maps of the spatial distribution of input data, model parameters and results quickly is of high value. Explorative spatial

data analysis, visual evaluation of data quality and map-based interpretation of intermediate or final results of the model calculations are important application fields of GIS-supported visualization tools.

The regionalization of hydrological information requires the acquisition, management and cartographic presentation of large spatial data sets and the development of suitable methods for analysing such data. Therefore, the application of GIS technology is an essential prerequisite to the successful work of the German DFG research programme on Regionalization in Hydrology and a challenge in finding enhanced or even new ideas of spatial modelling in hydrology (Streit & Kleeberg, 1996).

To simplify the management and exchange of spatial data, to analyse spatial data in a compatible software environment, and to exchange technical and methodology experience with each other, all members of the DFG research programme have come to agreement about the definition of a common GIS platform. A detailed analysis of the special demands and an analysis of available GIS, accompanied by tests of performance, were carried out in 1992. Chosen operational conditions were the possibility of execution on UNIX workstations, a broad palette of interfaces to database systems and other GIS, and a reasonable relationship of costs and performance. At that time, the best solution for the purposes of the priority programme was a combination of ARC/INFO and GRASS.

TOOLS FOR HYDROLOGICAL INFORMATION AND MODELLING

The working group at the University of Münster has been responsible for coupling the components of the GIS-platform, for developing a graphical interface for the simple use of this GIS environment and for providing special GIS-tools for the regionalization of hydrological data and models. Using the data structures and basic functions of ARC/INFO as a GIS kernel, the Arc Macro Language AML, and the ArcTools, a hydrological user shell, T₄HIM (Tools For Hydrological Information and Modelling), has been developed (Fuhrmann *et al.*, 1997). It offers a structured menu system reflecting the usual work flow in spatial hydrological analyses and a wide range of special GIS-tools for regionalization in hydrology, e.g. management of hydrological objects, DEM-based calculation of hydro-morphometric parameters, flow-dependent determination of topological relationships between sub-basins, methods for spatial aggregation, disaggregation and interpolation, and standard layouts for hydrological maps.

Scale invariant spatial transfer of information

A very important basis for all variants of regionalization is the scale invariant information transfer from single objects to an object set. Estimating means and variances of a set of objects for hydrological variables is a rather simple method. These statistical parameters are easy to use descriptors, but they cannot characterize the spatial distribution of the attribute values. Usage of statistical distribution functions is a well-known approach for taking into account the frequency or probability of values. In a strict sense, the ordinary distribution function is a non-spatial approach. To

describe spatial fields by their stochastic behaviour, spatial relationships between objects have to be considered, varying with distance and direction. Spatial autocorrelation and variogram analysis are keywords in this domain of exploratory spatial data analysis.

The estimation of point data by spatial interpolation methods or the application of regression methods for estimating unknown basin characteristics from measured catchment data, present more specialized problems of transferring information between spatial objects without changing the scale.

Upscaling spatial information

Changing from a micro- to a meso- or even macroscale of analysis and modelling means generalization. Generalization is an abstraction and simplification of reality or of an already available model (model reduction) and requires an aggregation of single object features to more general characteristics. Averaging of spatial data is not a real leap over scales in a strict sense of regionalization, because such a statistical data aggregation does not take into account the problems of semantic generalization and loss of information.

The aggregation of flow directions from a DEM is one example of an upscaling of hydrological characteristics, involving considerable loss of information and in many cases even a change of hydraulic context. Figure 1 gives an example from the Weser basin, which is the target basin for the DFG research programme. The original DEM

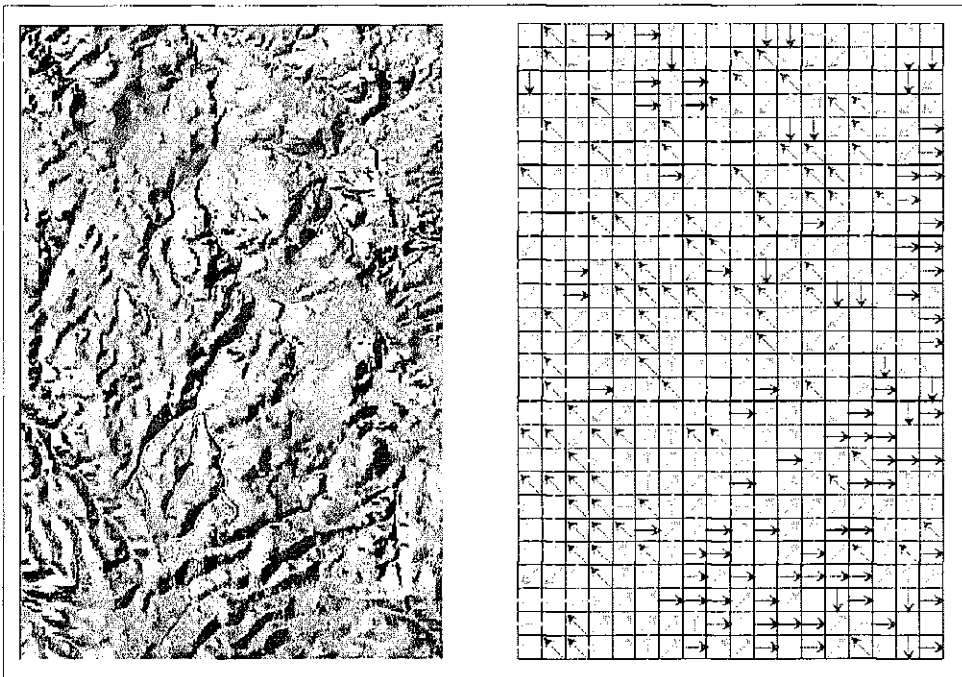


Fig. 1 Aggregation of flow directions from a DEM of the Weser basin.

(left side of Fig. 1) has a spatial resolution of about 30 m (German AMilGeo grid of 1 degree-second). For the mesoscale hydrological modelling in the Weser basin, this DEM has to be aggregated to a grid size of 1 km². Flow directions derived from this aggregated DEM by usual GIS algorithms show a distorted flow pattern (right side of Fig. 1). If the flow direction of the aggregated cell is calculated from the sub-cell in the original data set that has the highest amount of flow accumulation, the results are significantly better. Figure 2 shows examples for derived drainage basins using this T₄HIM aggregation procedure for flow directions, in comparison to the usual GIS-based calculation from averaged DEM data.

The spatially aggregated hydrological characteristics have scale dependent errors regarding their geometry, topology and attributes. It is very important to distinguish between the error terms of the original data and the inaccuracies introduced by the upscaling procedure itself. Unfortunately, few investigations into these questions of data quality, algorithm effectiveness and spatial error analysis of results, have been carried out in hydrology. As one of the results of the special research programme it must be stated that the problems of scaling up basic hydrological data, model parameters and models itself remain largely unsolved.

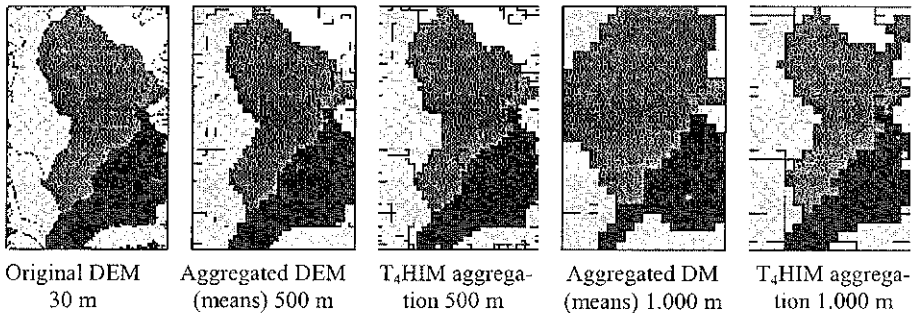


Fig. 2 Comparison of drainage basins derived from flow directions with aggregated DEM (usual procedure) and from the modified T₄HIM flow direction aggregation procedure.

Downscaling spatial information

Spatial downscaling may be even more ambitious, but it is a necessary research topic not only from a theoretical point of view. How can we disaggregate discharge volumes measured at the basin outlet, but composed of different runoff amounts from a lot of sub-basins upstream the gauging station? How can we derive the internal spatial variation of vapour concentration in a remotely sensed macro-pixel? In principle, these problems cannot be solved without having reliable hydrological models and adding spatially detailed information at the downscaling level. The nesting of small-scale into large-scale models may be a feasible approach. The DFG research programme has revealed considerable deficits in this field of hydrological research in Germany.

HYDROLOGIC VISUALIZATION SYSTEM HYDROVIS

The development and application of methods for the visualization of hydrological data and documentation of hydrological models used in the DFG research programme is another main objective of the GIS research group at the Institute for Geoinformatics in Münster. The spread of novel information and communication technology in the geosciences within the last decades has led to the increased collection, availability and use of spatial and temporal digital data. Alongside this development, electronic media, e.g. CD-ROM and online services, are used in the geosciences for the publication of research results and for distributing data. Electronic publications can consist of data without a viewer application on the lower end, or include a data specific complex information system with digital documentation, metadata information system, an integrated graphical user interface and sophisticated visualization techniques on the higher end.

The current innovations in the area of Visualization in Scientific Computing (ViSC), Geographical Visualization (GeoViSC) and modern cartographic publication techniques, formed one research field in the course of the DFG research programme. At the Department of Geoinformatics a digital Hydrologic Visualization System "HydroVIS" is designed for the hypermedial visualization of regionalization methods, hydrological models and spatial data in the Weser basin. The visual components of HydroVIS offer a variety of advantages, e.g. the integration of cartographic animation for spatial and/or temporal hydrological processes, interactive digital maps, context sensitive links between diverse digital media, a metadata based information and help system. Examples can be found on the home page of the Institute for Geoinformatics (<http://ifgi.uni-muenster.de>). HydroVIS was published in 1999 as a Windows-based system on CD-ROM (in German) which can be ordered free of charge by e-mail from the Institute of Geoinformatics, or as volume 3 (July 1999) of the IfGIprints Series (cost 20 Euro, including the CD), available from the Institute.

PERSPECTIVES FOR GIS-BASED REGIONALIZATION

One of the general results of the DFG research programme after four years of work is the sobering experience that GIS today has a lot of conceptual and practical shortcomings which hinder hydrologists in using GIS tools more efficiently.

Almost all GIS have a Relational Data Base Management System (RDBMS) or a flat file system for storing geometric, topologic and thematic data. These database systems have standard data types and data structures. But for spatial analysis and modelling, more complex data structures such as line segments for stream reaches or polygons for river basins are needed. The paradigmatic change in computer science from relational to object-oriented data models opens new chances for modelling spatial hydrological data. Object-class hierarchies with inheritance of features will help to overcome the separate modelling and storing of geometric, topologic and thematic data which is typical for current GIS applications (Becker *et al.*, 1996).

Time plays an important role in analysing and modelling hydrological processes. In contrast, GIS originally are spatial information systems with strong roots in cartography and CAD. They are designed for modelling static situations. The usual

“temporal data model” for representing space-time variations in standard GIS is a series of snapshot maps. But there are theoretical approaches and prototypic developments for temporal GIS, using object-oriented modelling techniques: The time domain is modelled in multiple dimensions like valid time (time when events occur in the real world) and transaction time (time when the event is stored or modified in the database). Basic spatio-temporal GIS-functions (e.g. transmission, expansion, displacement,) have to be developed for modelling hydrologic processes (Peuquet & Quian, 1996).

Currently in GIS, three-dimensional hydrological objects are approximated by two-dimensional data models, ignoring the third dimension or substituting it by an attribute. Typical examples are multi-layer models of snow cover or soil moisture distribution, approximating the three-dimensional (3D) reality by a series of more or less independently modelled two-dimensional (2D) layers. For a more realistic spatial modelling of runoff processes, generic three-dimensional GIS with 3D-pixels (voxels) and 3D vector objects (boundary representations, polyhedron primitives) are necessary. Examples for 3D GIS-like systems are known from geology, oil exploration and climatology (Bernard & Streit, 1996).

Most existing GIS are large monolithic and isolated systems. They allow neither an easy access of spatial and temporal data from a variety of sources, nor a full integration of GIS and hydrological models with different modules. But hydrologists need a high degree of inter-operability between GIS, modelling systems, image processing systems, statistical analysis packages, and digital cartography systems according to the principle of “plug-and-play”. A very promising project is the Open GIS consortium OGC which is a union of GIS developers, database companies, data suppliers, government agencies and universities. The main goal of OGC is the definition of an “Open Geodata Interoperability Specification” (OGIS) for a distributed access to geodata and open geoprocessing systems (Buehler & McKee, 1996).

These current trends in GIS technology promise better usability for hydrological applications in the not-so-distant future. They provide a new challenge and new opportunities for hydrologists concerned with spatio-temporal data analysis and process modelling.

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