International Conference on

Application of Geographic Information Systems in Hydrology and Water Resources Management

HydroGIS '96

Vienna, Austria
April 16 - 19, 1996

Edited by

H. Holzmann
H.P. Nachtnebel
Institut für Wasserwirtschaft, Hydrologie und konstruktiven Wasserbau
Universität für Bodenkultur (BOKU)
Nussdorfer Laende 11, A-1190 Vienna, Austria

Poster Paper Volume of an international conference HydroGIS '96 held in Vienna, Austria, from 16 to 19 April 1996. This conference was jointly organized by:

Institut für Wasserwirtschaft, Hydrologie und konstruktiven Wasserbau,
Universität für Bodenkultur; IWHW-BOKU, Vienna

the International Commission on Groundwater (ICGW) of the International Association of Hydrological Sciences (IAHS)

the International Committee on Remote Sensing and Data Transmission (ICRSDT) of the International Association of Hydrological Sciences (IAHS),

the United Nations Educational, Scientific and Cultural Organisation (UNESCO) - Division of Water Resources

The conference was sponsored and supported by:

The International Association of Hydrologists (IAH) , the International Ground Water Modeling Center (IGWMC), the International Institute of Applied System Analysis (IIASA) - Austria, the American Society of Testing and Materials (ASTM), the American Society for Photogrammetry and Remote Sensing (ASPRS), the Austrian Hydrological Society, the International Association for Hydraulic Research (IAHR).

The convenors of the conference would like to express their thanks for financial support obtained from the following companies and institutions:

UNESCO, Division of Water Resources
Datamed GmbH, Vienna - Austria (vendor of ARC/INFO)
Austrian Airlines, official carrier for the conference
Bank Austria, Vienna
Mayer and Governor of Vienna
The Austrian Federal Ministry for Agriculture and Forestry

GIS-BASED HYDROLOGICAL MODEL OF THE KISALFÖLD AREA (HUNGARY)

Z. VEKERDY* **, A.M.J. MEIJERINK* & J.C. VAN DAM***

* International Institute for Aerospace Survey and Earth Sciences (ITC)
350 Boulevard 1945, P.O.Box 6, 7500 AA Enschede, The Netherlands

** Water Resources Research Centre Plc. (VITUKI)
H-1095 Kvassay J. út 1, Budapest, Hungary

*** Delft University of Technology
Stevinweg 1, P.O.Box 5048, 2600 GA Delft, The Netherlands

Abstract The regional hydrology of the Kisalföld area (Hungary) was captured in a GIS (ILWIS), which played a role of central integration medium and supported with its analytical tools the determination of boundary conditions and subregional processes. The research concentrated on methodological issues, with a basic assumption that it is possible to shortcut some difficulties of hydrological model calibration with spatial analysis in a GIS environment. Spatial analysis was used to determine the characteristics of hydrological variables: to characterize the continuity of the cover layer, to assess recharge by various methods and to study the propagation of the effect of the river stages in the groundwater. Hydrological models (FLOWNET, HYDRUS, MODFLOW) were used to simulate the subregional processes and the regional groundwater flow system. The coupling of data bases, spatial analysis, rules and models constitutes, in fact, a hydrologic information system. The system enables the evaluation of the modelling results. Methodological conclusions are presented about the accuracies and the effects of up- and down-scaling in the construction of hydrologic information systems.

INTRODUCTION AND BACKGROUND

A study was carried out to investigate how spatial analysis in a GIS environment improves the insight into the hydrological processes of alluvial regions, where surface waters and groundwater are strongly interrelated. The following objectives were formulated:

- To improve existing methods for obtaining insight into the hydrology of alluvial areas, on the basis of analysis in a GIS environment.
- To determine the possibilities and limitations of GIS-assisted spatial analysis in hydrological spatial process modelling.
- To determine the possible effects of the changes of the water levels in the main rivers on the hydrological and ecological systems of a selected alluvial region, the Kisalföld.

The study focused on mainly methodological issues. The Kisalföld (Small Hungarian Plain), was chosen as the study area because a very rich database is available from this region.

The Kisalföld is of alluvial origin. It is located in the centre of a down-warping tectonic basin which was filled up gradually in the Tertiary by mostly fine-grained marine and lacustrine deposits. Sandy and gravelly fluvial deposits covered them in the Quaternary, reaching 700 m thickness at the central part of the basin. This alluvium contains one of the largest freshwater reserves of Central Europe [Erdélyi, 1994]. The aquifer is covered by a thin layer of fluvial deposits of finer grain size, the 'cover layer'.

The investigated area of the Kisalföld, the Győr Basin (*Figure 1*) occupies the right bank side of the alluvial fan of the Danube and the whole alluvial fan of the Rába river.

Due to the construction of a hydropower station, the largest part of the discharge of the Danube has been diverted into an isolated side channel in 1992. Since the groundwater and the surface waters are in strong contact in the Győr Basin, the present study examined the possible effects of the diversion on the groundwater heads and the fluxes between the hydrological subsystems.

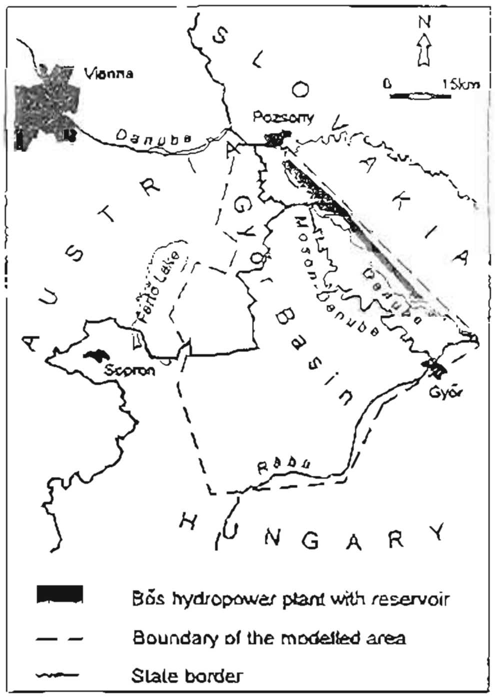

Figure 1 *Location of the investigated region*

TOOLS AND METHODS APPLIED FOR THE ANALYSIS OF THE HYDROLOGICAL SYSTEM OF THE KISALFÖLD

Data from several different sources have been integrated in a GIS environment (based on the ILWIS GIS/RS package[1]) containing lithological, topographical, land use, soil and geoelectrical maps and remotely sensed data. The tabular database contained time series of river stages and groundwater levels, meteorological parameters and other, time invariant point-like data as soil and lithological characteristics.

Spatial statistics and remote sensing methods were used in the *preparation of the input data* for the hydrological analysis.

Since the geometric and hydraulic characteristics of the cover layer strongly affect the fluxes across the groundwater table (the recharge and the upward groundwater loss).

[1] ILWIS: Integrated Land and Water Information System, product of the International Institute for Aerospace Survey and Earth Sciences (ITC, The Netherlands)

spatial analysis was carried out to find the optimal mapping methods of the thickness and the hydraulic conductivity of this layer.

Besides the cover layer, the vegetation also has an effect on the fluxes across the groundwater table, due to its root water uptake. Land use maps contain the main land use types, but large differences may occur in the actual rooting depth within the land use types, especially in the arable lands. In the Kisalföld these differences are emphasized in spring, when winter crops are strongly developed but spring crops have not yet emerged. A separation method of these two categories was applied based on density slicing of a normalized difference vegetation index (NDVI), calculated from a Landsat MSS satellite image. This was followed by assigning vertical root distribution values to the separated categories.

In order to describe the hydrological processes of the region in a GIS environment it was necessary to partly couple various modelling approaches and various software packages. The following approaches have been used for the determination of the fluxes across the external and internal boundaries of the Quaternary aquifer of the Kisalföld:

- The lower boundary condition is formed by the flow between the Quaternary alluvium with high permeability and the underlying Pannonian deposits with low permeability. 2D steady state models have been worked out for various sections using the computer code FLOWNET [Van Elburg et al., 1989]. The model calibrations were based on the hydrodynamical sections by Erdélyi [1979]. It could be assessed that the flow across the lower boundary of the Quaternary aquifer is insignificant, being not more than 4% of the annual net flux at the groundwater table.
- Two methods have been used to determine the parameters which describe the fluxes across the upper boundary, the groundwater table:
  - Regionalization by a semi-empirical method, which was based on relational operations between raster maps in a GIS, using values taken from literature [Tahy, 1991, Márton, 1994] and from experience obtained at hydrological experimental sites [Simonffy, 1994]. The maps were used as a quick estimate of the magnitude of the fluxes across the groundwater table.
  - Regionalization based on a finite element 1D unsaturated flow simulation computer code, HYDRUS, [Kool & Van Genuchten, 1991]. Measured soil moisture data of monitoring sites [Vargay, 1985] have been used for the verification of the model parameters. Mapping units were formed by crossing the model parameter maps (vegetation, soil characteristics) in the GIS. Then the flow through the unsaturated zone was simulated for every mapping unit. The results were mapped and used as input for the 3D groundwater modelling.
- The rivers have profound effect on the propagation of the bank storage. Regionalization was carried out to get an insight into the extent of the zones effected by the river stage fluctuations. In the (semi-)confined parts of the aquifer the bank storage propagation was investigated by using Leenen's [1994] analytical solution method of the normalized 1D semi-confined groundwater flow equation. For phreatic conditions the analytical solution of the phreatic flow equation introduced by Edelman [1947] was used. The methods have been verified along measured sections perpendicular to the largest river, the Danube. A map of the regions influenced by the largest rivers of the Kisalföld has been calculated in the GIS, using the hydraulic parameter maps of the Kisalföld and measured stage data of the rivers. The results were compared with calculated lag-correlations between the river stages and the

groundwater responses in observation wells. The map of the river influenced zones supported the qualitative reasoning during the calibration of the regional groundwater flow model.

- A 3-D groundwater flow model based on the computer code MODFLOW [McDonald & Harbaugh, 1988; McDonald et al., 1991] provides the framework for the comprehensive groundwater hydrology of the area. The boundary conditions and the parameters of the subregional processes, which had been determined in the former steps, were used as input. During the calibration the GIS has been used partly as a user interface for the visualization of the model output, and partly for the analysis of the discrepancies between the output and the modelling target.

DISCUSSION

The following discussion focuses mainly on the methodological aspects of the hydrological analysis and modelling in a GIS, and only the most important site specific results are mentioned here.

Data preprocessing and spatial analysis of hydrological variables in a GIS environment

Data integration is one of the most powerful functions of a GIS. This has been intensively used in the construction of a raw data set for the Kisalföld. Data transformations were restricted to geometric and sometimes temporal transformations, and data model transformations of the raw data (such as vector to raster conversion) were applied only when a specific application required it in the later steps.

Flexibility in access to the data is one of the most important requirement from a GIS in data preprocessing. There is no need for a complex database structure because it would result in a data (structure)-driven situation. In fact, a database with established spatial and structural links can be designed only on the basis of the comprehensive analysis of the hydrological system. Thus the applicability of the object-oriented data structure – which is a popular field of the research in GIS – in this case is very limited: an object-oriented approach needs the exact determination of the objects and their relationships, but these may become known only as a result of the hydrological analysis.

Spatial analysis highlights the spatial characteristics of the variables. Statistical methods were used to qualitatively describe the spatial characteristics of hydrological variables. In the case of the cover layer thickness data of the Győr Basin, the sufficiency of the network was evaluated by analysing the effect of different *observation network densities* on the representation of the subregional spatial variances. The analysis highlighted differences in the spatial characteristics of the cover layers of the Danube and the Rába alluvial fans. The two fans were, therefore, treated separately in the later steps.

Variogram analysis (or the analysis of any other spatial continuity function) is the best way to describe the *spatial continuity* of a variable. Moving window statistics highlights the *spatial anomalies* of a variable by calculating the local descriptive statistics, such as the local means or the coefficients of variation. These methods were also used for the analysis of the cover layer of the Győr Basin.

Qualitative classification of the spatial characteristics of the drainage network (i.e. drainage density) was also used in the calibration of the groundwater flow model of the Győr Basin.

Regionalization is the most *complex spatial analysis* method. It can be described as the derivation of one categorical spatial variable from several other spatial variables. This has been used for the determination of the boundary processes, based on a method modified from Simmers [1984].

Hydrological system description, subregional and boundary process analysis

Analytical and visualization functions of GIS were used to describe the hydrological system and to analyze the subregional and boundary processes.

The processes of the upper boundary of a phreatic groundwater system are the surface recharge and upward loss from the groundwater. These fluxes across the groundwater table cannot be measured directly on a regional scale, therefore they had to be deduced from other variables.

It is relatively easy to implement *empirical rules and transfer functions* in a GIS environment, but their disadvantage is that they are not based on objective laws. Thus their accuracy depends on subjective factors. In spite of this fact they were found to be useful for a preliminary assessment of the magnitude of the fluxes across the groundwater table.

Physically-based numerical methods are usually more complex than the empirical transfer functions. The applied quasi-steady-state simulation of the flow in the unsaturated zone was more objective than the empirical rules, but it suffers from the scale effect. Point measurements had to be used for the calibration of the hydraulic parameters of the flow medium. Such a calibration may reflect the local variance of the hydraulic parameters, which is then erroneously extrapolated to a large area, e.g. a mapping unit.

It can be concluded that the recently available methods and transfer functions – simple or complex makes no difference – cannot describe the processes in the unsaturated zone on a regional scale with a high accuracy.

Scaling and representativity problems occurred in the regionalization of the river effect on the groundwater too.

Groundwater modelling in a GIS environment

Groundwater modelling is the key to the quantitative description of the hydrological system of alluvial areas. The most important GIS functions which support groundwater modelling are summarized in *Table 1*.

Table 1 GIS functions in the different steps of groundwater modelling

Modelling step		GIS function
Preprocessing	Data collection	Data integration: retrieval from external databases; import from different file formats, merging maps
	Identification of area to be modelled (topographic map – geometric background)	Digitizing; raster–vector and vector–raster conversions
	Mesh design (model code specific step)	Interactive editing of segment and polygon maps, coordinate transformation; rasterization; map calculations
	Creation of surfaces (continuous spatial variables, e.g. top and bottom of a layer)	DEM generation; map calculations; neighbourhood calculations
	Regionalization (categorical spatial variables), modelling of subprocesses	Map calculations; spatial statistics
	Reconstruction of 3D objects (e.g. aquifers)	Spatial statistics; creation of and data retrieval from 3D data sets; visualization of 3D surfaces, sections
	Transfer of assembled data to the model code (input file generation)	Automation by programming capabilities (batch files, macros, modelling language) for the geometric control of input data and file format conversion
Calibration, sensitivity analysis, verification, prediction	Evaluation of the result	Visualization; overlaying; retrieval of values from maps; statistics of a whole map; statistics of selected areas of one or several maps; map calculation; section editing from 2D and 3D data, time series analysis; animation of the results of consecutive runs; animation of the results of consecutive time steps
	Modification of parameters	Visualization; overlaying Editing of map values Map calculation
	Scenario analysis	Visualization; overlaying; retrieval of values from maps; statistics of a whole map, statistics of selected areas of one or several maps; animation of the results of consecutive time steps

The most important point in coupling a GIS and a groundwater flow simulation code (or any other hydrological model using spatially distributed parameters) is that the analytical tools of the GIS must have direct access to the input and output data structures of the simulation code. This can be solved by data transfer programs. Such a coupling is more a technical than a scientific issue: some specific functions have to be added to a general purpose GIS software to support hydrological analysis. These functions may help the determination of the model geometry, and may provide a framework for routinely repeated operations such as visualization, statistical calculations etc.

Hydrological system of the Kisalföld

The results of the comprehensive analysis of the hydrological system of the Kisalföld were the basis for constructing the steady-state groundwater flow model of the region.

The recharge and upward groundwater loss values of the regionalization and the calibrated model were compared. It was found that the regionalization methods resulted in an overestimate of those parameters, which have an effect on the simulated upward groundwater loss.

Some discrepancies were also found between the results of the regionalization of the river-influenced zones and the calibrated groundwater model.

Subregions – termed as water budget units – were formed to calculate the subregional fluxes. These units were delineated on the basis of drainage densities and the widths of the river-influenced zones. This subdivision of the Győr Basin provided a basis for a detailed analysis of the interactions of the different parts of the hydrological system.

Two scenarios were analyzed: the 'initial' scenario which simulated the mean annual groundwater heads and fluxes of the period 1979–89, and the 'diverted Danube' scenario, which simulated the mean annual situation after the diversion of the Danube. The analysis of the scenarios showed that the rivers play a more important role in the recharge to the groundwater than the surface recharge, especially on the Danube alluvial fan. It was found that a considerable drop of the annual mean groundwater heads occurs in the northern and middle part of the Szigetköz if no artificial recharge measures are applied.

Because of its equidistant grid of 1000 m spacing, the developed model describes only the regional processes. This resolution does not allow the simulation of the local processes, but this regional model may serve as a starting point for modelling local flow and transport processes in the future.

GENERAL METHODOLOGICAL CONCLUSIONS

On the one hand, evidence has been provided in this study of the important effects of local variations of the hydrological variables, e.g. hydraulic properties of sediment types, cover layer thickness. A part of these local variations cannot be described because of practical and theoretical limitations:

- Increasing the number of observations within a practically manageable range does not necessarily improve the accuracy of the representation of some variables, as was shown in the case of the cover layer thickness.
- Deterministic simulation models involve simplifications, which neglect some local effects. Another source of problems is that the point measurements which are used for model calibration cannot describe all the spatial variations of the variable, therefore, extrapolation from them may cause errors.

The conclusion is that deterministic up-scaling is not a proper approach for the modelling of regional hydrological processes.

On the other hand, it was demonstrated that it is possible to simulate regional hydrological processes by deterministic groundwater flow models in alluvial areas. The effects of the unknown local variations can be eliminated by the calibration of the model. Approaching hydrological processes from regional to local scale is the most appropriate way, i.e. down-scaling is the best approach in hydrological analysis.

On a more general level, it can be concluded that protocols for hydrological analysis – like the one suggested by Simmers [1984] for regionalization – help us to understand the information flow through the steps of the procedure in general, but do not provide a robust guide to solve each problem. Instead of suggesting another protocol, the existing methods may be improved by identifying the 'bottle necks' of the information flow. It was found that such a bottle neck occurs in the first steps of the analysis, namely in the reconstruction of the spatial hydrological variables from the measured data. The spatial characteristics of the variables, therefore, have to be analyzed and the optimal representation method has to be determined. This is the field where GIS technology can have the most important contribution to hydrological analysis.

ACKNOWLEDGEMENTS

The present article is the summary of the Ph.D. research of the first author [Vekerdy, 1996] under the supervision of the other two authors. The research was financed by the International Institute for Aerospace Survey and Earth Sciences (ITC), Enschede, The Netherlands, with the support of the Water Resources Research Centre (VITUKI), Budapest, Hungary and the Cartography Department of the Eötvös University, Budapest, Hungary. The authors would like to express their gratitude to Professor Dr. István Klinghammer for his support.

REFERENCES

Edelman, J.H., 1947: Over de berekening van grondwaterstroomingen (About the calculation of groundwater flow), Ph.D. thesis, Delft University of Technology, The Netherlands

Erdélyi M., 1979: Hydrodynamics of the Hungarian Basin, VITUKI Proceedings nr. 18. VITUKI, Budapest, Hungary, 82 p.

Erdélyi M., 1994: Hydrogeology of the Hungarian upper Danube section (before and after damming the river), Natural History Museum, Budapest, Hungary, 115 p.

Márton T., 1994: Telítetlen zónás szivárgási modell kalibrálása észlelési adatok alapján a Duna-Tisza-közén (The calibration of an unsaturated zone flow model based on measurements for the Duna-Tisza-köze), (internal report, manuscript), VITUKI. Budapest, Hungary, 17 p.

McDonald, M.G., A.W. Harbaugh, 1988: A modular three-dimensional finite-difference ground-waterflow model, Modelling techniques, book 6, USGS

McDonald, M.G., A.W. Harbaugh, B.R. Orr, D.J. Ackerman, 1991: A method of converting no-flow cells to variable-head cells for the U.S. Geological Survey modular finite-difference ground-water flow model, USGS Open file report 91-536, USGS, USA, 99 p.

Kool, J.B., M.Th. Van Genuchten, 1990: HYDRUS - One-dimensional variably saturated flow and transport model, including hysteresis and root water uptake (software manual), HydroGeoLogic Inc., Herndon, Virginia, USA

Leenen, J.D., 1994: Voortplanting van grondwaterstadsfluctuaties, met het effect van een hoogwatergolf als bijzondere toepassing (Migration of ground water fluctuation as a special application to the effect of a high water wave), H_20, vol. 27. nr. 5, pp. 128-131

Simmers, I., 1984: A systematic problem-oriented approach to hydrological data regionalization, Journal of Hydrology, 73, pp.71-87

Simonffy Z., 1994: Personal communication at the Water Resources Research Centre (VITUKI), Budapest

Tahy Á., 1993: Evaluation of the recharge and the discharge conditions in the Danube-Tisza Interfluvial using geographical information system, (M.Sc. thesis), European master degree course in environmental science and engineering (TEMPUS Programme), Budapest, Hungary, 30 p.

Van Elburg, H., G.B. Engelen, C.J. Hemker, 1989: FLOWNET version 5.1 - User's manual, Manuscript, Free University, Amsterdam, The Netherlands

Vargay Z., 1985: GNV szigetközi fedőréteg vizsgálat – Nedvességmérő hálózat üzemeltetése a Szigetközben, adatfeldolgozás (Gabcikovo-Nagymaros barrage system, Examination of the properties of the cover layer – Soil moisture measurements and the processing of the data) Research report, No. 7623/1/9-II, VITUKI, Budapest, Hungary, 10 p.

Vekerdy Z., 1996: GIS based hydrological modelling of alluvial regions, using the example of the Kisalföld (Hungary), Ph.D. Thesis, Eötvös University, Budapest, Hungary, 180 p.