# Processorientated water balance modeling of two headwater catchments of the Elbe river system, Germany

Dipl.-Geogr. Christian Michl
Institute of Geography
Geoinformatics, Geohydrology und Modeling
Löbdergraben 32
07743 Jena, Germany
Tel.: +49-3641-948856
Fax.: +49-3641-948852
e-mail: c5chmi@geogr.uni-jena.de

**Abstract** The concept of Hydrological Response Units (HRU's) and their delineation by GIS-analysis to two headwater catchments (A = 4.22 km$^2$) of the Thuringian Forest in central Germany to model the impacts of afforestration is presented. HRU's are designed as object orientated model entities and can be used in regional hydrological modelling of different scales. To model the systems dynamic the PRMS/MMS models was adopted and HRU's were delineated by GIS overlay and DEM (5m x 5m grid size) analysis to classify pedo-topo-associations and different cover density classes. The PRMS/MMS model was parameterized that rainfall input not contributing to evapotranspiration was routed to a common subsurface storage , which drained by interflow to the shallow groundwater aquifer in the valley floors, which in turn drained to the channel network. The model was first calibrated on two spatial discretisation of 9 and 17 HRU classes, using a four-year daily data time series (1979-1982). The achieved parameterization is at the time used to run the model over a daily data time series from 1959 till 1996. At the beginning of that time intervall about 70% of the spurce forest was planted. The longterm time series will be used to assess the concept's and model's capability as well as the sensitivity of the number of the HRU classes to simulate changes in the vegetation cover, such as an upgrowing forest. Future work will concentrate on the determination of variable parameter sets to account for the change in vegetation cover over the years. Futhermore due to the integration of remote sensing techniques the concept of the model will be applied to other north exposed catchments in the Thuringian Forest.

## 1 INTRODUCTION

In recent years the application of hydrological models has added a lot of knowledge to the understanding of the natural system [Haan et al., 1982]. The model performance thereby highly correlates with the available data from field studies. Publications by Kirkby [1978], Leavesley et al. [1983] and Anderson & Burt [1990] show examplarily the gained conceptual and physical understanding of watershed hydrology. Through the decades, some hydrological models have become more distributed and physically based to account for this heterogeneity of the hydrological system.

The modulary structured precipitation runoff model PRMS/MMS [Leavesley et al., 1983] applied in this study fulfills this condition allowing model adaptions to various hydrological regimes. To deal with the heterogeneous assembly of land surface data geographic information systems provide a set of tools to automize model parameterization [Maidment, 1991].

Behind this background two well studied headwater catchments in central Germany were selected to simulate the systems response under an upgrowing forest using current model and GIS strategies.

### 1.1 Objectives

The objectives of this study, are: (i) to develop a HRU concept for headwater catchments based on the analysis of the hydrological system using the two test catchments of the *Schmücker Graben* and the *Steinbach*; and (ii) to simulate the hydrology of both basins in respect to the upgrowing forest with the PRMS/MMS model.

### 1.2 Study area

The study area is located on the northern slope of the Thuringian Forest, a montainous area in central Germany. It covers the headwater catchments of the *Schmücker Graben* (A=2.92km²) and the *Steinbach* (A=1.32km²) of the Gera-Saale-Elbe-system. The elevation ranges from 714 m at the confluenece of both streams to 982 m at the *Großen Beerberg*, the highest peak in the Thuringian Forest. Both valleys drain in an almost northern direction and can be clearly differentiated by their watersheds. The upper valley of the *Schmücker Graben* is characterized by gentle slopes which are getting steeper in the lower part, whereas in the *Steinbach* steep slopes are found throughout the whole catchment.

## 2 ANALYSIS OF THE HYDROLOGICAL SYSTEM

### 2.1 Basin Characteristics

The climate of the study area is oceanic dominated. During the summer, convective storms are frequent and in the winter half-year advective rainfall is dominant. The longterm annual precipitation is 1340 mm with an average anual temperature of 4.3 Celsius. Above an altitude of 700 m a snowcover above 1cm can be expected in 120 - 125 days a year. The snow accumulation normally starts in the middle of November and lasts till mid or end of April.

Geologically, the study area consists alternating of quartz porphyry and porphyry tuff. Surveys have showed that deep percolation is negliable and both systems react as a big lysimeter. Recent studies pointed out that the hydrological dynamic is influenced mainly by the interflow and can be described as follows: (i) the convex tops of the highest elevations are structured in a way that the fractured system of the quartz porphyry is filled by loamy material which impedes the infiltration of precipitation and leads to a downslope water movement; (ii) in depressions the water gets stored which causes the development of wetlands; (iii) along the slopes the water path follows the consolidated layers in the cover of the debris and feeds many little springs; (iv) the layers in the cover of the debris are tegularly arranged which favours an echeloned flow of the percolating water.

As outlined in the introduction the change of the vegetation cover is one of the main topics of the study. The vegetation analysis is based on intensive studies from Schlüter [1969] and the data base of the forest service. Schlüter used indicator plants to distinguish areas of different soil moisture. His results were compared to infiltration measurement data by Stephan [1968]. Schlüter [1969] differentiated six different habitat locations concerning their hydrological characteristics (spring fens, high bogs, mostly wet, intermediate wet, intermediate dry and dry locations). His study showed that the low number of different, modest species is mainly caused by the water balance. Stephan came to the same conclusions and showed that the spatial distibution of different species can be clearly correlated to the morphologically stimulated groundwater occurrence. Schlüter and Stephan [1968] summarized that the mostly wet and spring fen habitats were found in reception basins, in small depressions and the bottom contour lines. The intermediate wet and dry habitats show a water balance based but aspect independent vegetation distribution along the plains and slopes. Steeper slopes lead to a fast groundwater discharge and a concentration of dry habitats.

These former vegetation and moisture characteristics are essential to get an understanding for the water balance modeling over time and are connected to the data of the forest data base. This data base consists of stands information such as heights, widths, LAI, cover density etc. and is updated every 5 years for forest production planning.

### 2.2 Concept of the data base

For the study area an information system was build up to manage the data handling of the time series and the spatial distributed data layers. The time series analysis is done in the data base system ORACLE. The data pool consists at the moment of the following:(i) daily runoff of two gaging stations since 1959; (ii) groundwater levels of 11 monitoring wells for different time steps (continuous, weekly, monthly); (iii) daily precipitation data at the confluence of both torrents since 1959; (iv) decade values of 12 totalisators in the *Schmücker Graben* catchment for the years 1979 to 1982; (v) daily hydrometeorological data of a station from the German weather service just outside the study area since 1978; and (vi) measurements of soil moisture and snow cover.

Concerning the spatial distributed data an ARC/INFO data base was constructed which uses the topographic data of the German ordnance survey as georeference. Additionally a DEM on a 5m x 5m grid was used. At the moment the following data layers are available in the GIS data base: (i) layers of geology, geomorphology, slope and aspect; (ii) vegetation and soil moisture maps; (iii) different maps generated from the forest data base; (vi) scanned topographic and forestry maps; and (v) plans and visual material of the field instrumentation and the catchments.

As visualisation and interface to the data base ORACLE ARC/VIEW and its macro language AVENUE is used.

## 3 RESULTS

### 3.1 Delineation of HRU's

In Fig. 1 a basin segment with its subsystem storages and their interlinked water fluxes is shown. The schematic presentation can be seen as an abstraction of the natural hydrological systems of the *Schmücker Graben* and the *Steinbach*. The different subsystems such as topography, soils, geology and vegetation are adding to a three-dimensional physiographic hetero-

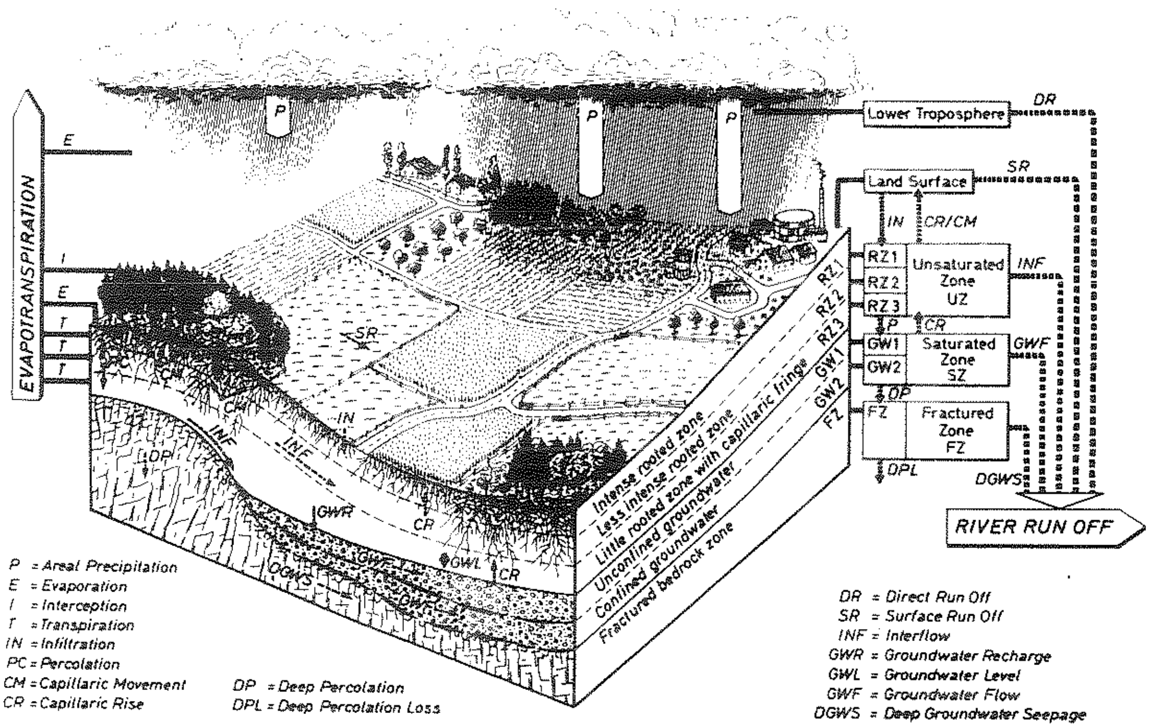


Fig.1 Schematic presentation of basin subsystem storages and their interlinked water fluxes to delinate HRU's [after FLÜGEL, 1995]

geneity that can be grouped together to different associations. Regarding the vegetation cover figure 1 clearly shows that each vegetation class is located on a specific topo-pedo-geological association forming a unique entity in the basin. After FLÜGEL [1995] these unique entities are defined as Hydrological Response Units:

*"Hydrological Response Units are distributed, heterogenously structured areas with common land use and topo-pedo-geological associations controlling their unique hydrological dynamics."*

Based on the system analysis and the understanding of the hydrological dynamics of both catchments, two different HRU classifications were delineated for the modeling application. They are shown in Fig.2 and Fig.3 and can be interpreted as follows:

In both cases the geology being very homogenuous within the two basins was not taken into account. The topo-pedo associations were considered by using two slope classes (slope 1 = 0-7 with deeper soils and slope 2 > 7 with shallow soils). A more detailed differentiation in the topo-pedo sequence could be achieved by generating soil classes from Schlüter's soil moisture classifications. According to his habitat locations concerning the hydrological dynamics the spring fens and high bogs were grouped as wetlands, the mostly wet locations joined with a 10 m stream buffer generated from the DEM as gleysoils and the remaining moisture class as podzol. The use of Schlüter's soil moisture classification additionally takes the vegetation into account from which the soil moisture classes were derived. Furthermore the cover density (cd in Fig. 2 and Fig.3) was used as thematic layer to consider the effects of the upgrowing forest which controlls the interception and evapotranspiration. Cover density was devided into three classes (grassland, low density of the tree cover and high density of the tree cover). In Fig.3 an additional aspect layer was added to place more emphasis on the snowmelt process. The aspect was hereby devided into a northern (0-90° and 270-360°) and a southern (90-270°) exposition.

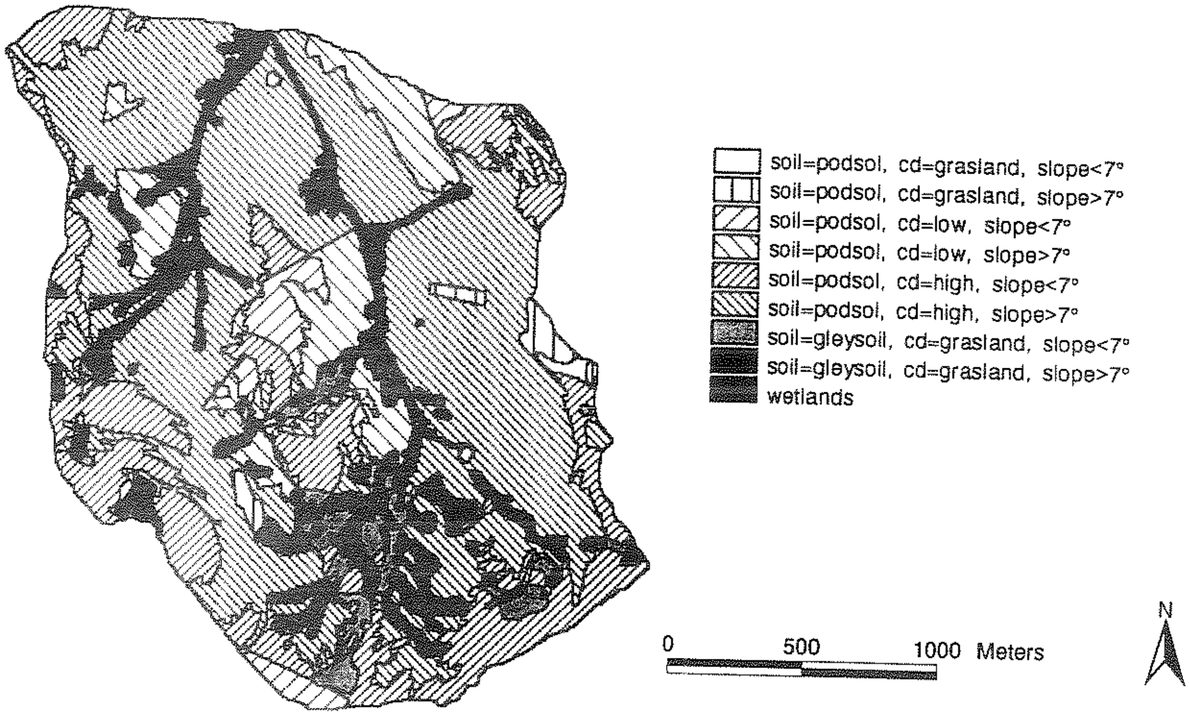


Fig.2 GIS overlay of 9 HRU classes based on the thematic layers of soil, vegetation cover and slope

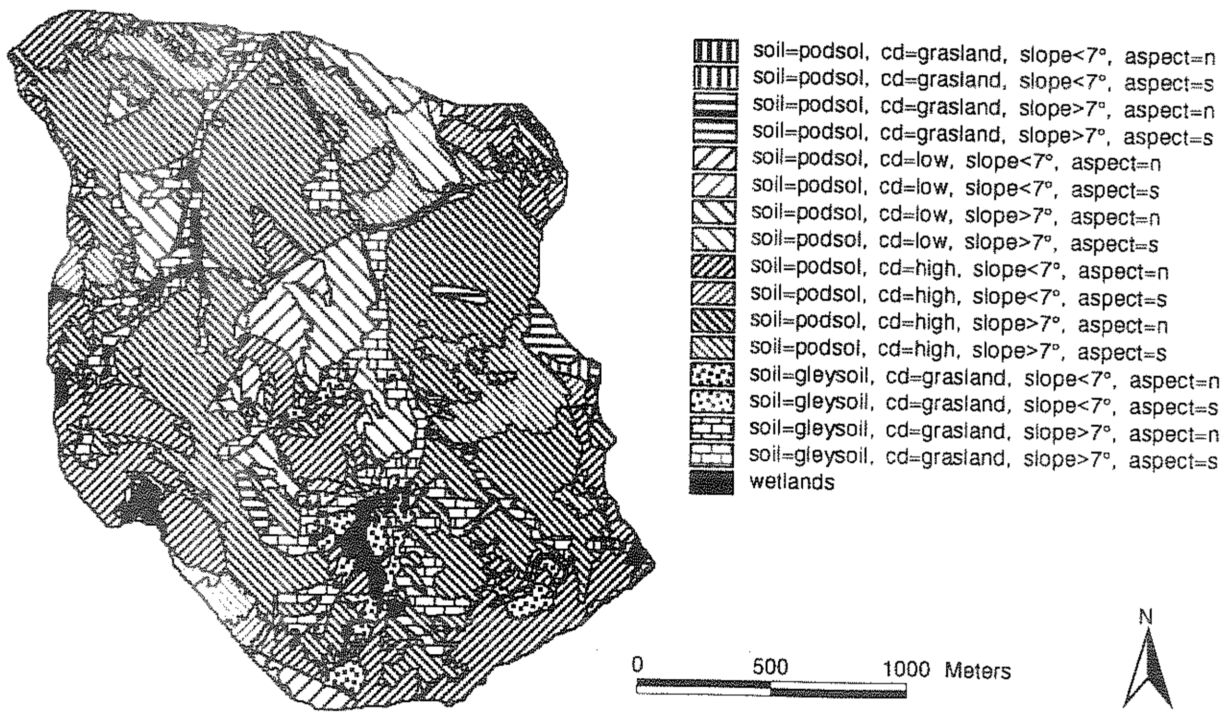


Fig.3 GIS overlay of 17 HRU classes based on the thematic layers of soil, vegetation cover, slope and aspect

In Tab.1 the physical properties of the HRU-9 classification is summarized.

| HRU | Soils | cover density | Slope [%] | Mean elevation [m] | Mean slope [%] | Area [km²] |
|---|---|---|---|---|---|---|
| 1 | podzol | grassland | < 12 | 958,47 | 8,96 | 0,0135 |
| 2 | podzol | grassland | > 12 | 930,10 | 23,48 | 0,0579 |
| 3 | podzol | low | < 12 | 889,18 | 8,58 | 0,1263 |
| 4 | podzol | low | > 12 | 853,68 | 26,38 | 0,3550 |
| 5 | podzol | high | < 12 | 922,67 | 8,58 | 0,8335 |
| 6 | podzol | high | > 12 | 872,47 | 25,29 | 2,0848 |
| 7 | gley | grassland | < 12 | 895,03 | 9,63 | 0,1410 |
| 8 | gley | grassland | > 12 | 852,85 | 24,97 | 0,4680 |
| 9 | wetlands | all | all | 893,37 | 12,40 | 0,0826 |

Tab. 1: Physical properties of the HRU-9 classification in Fig.2

### 3.2 MMS/PRMS Application

Both HRU delineations were tested using the PRMS/MMS model. A daily data time series from 1979-1982 were used for model calibration and parameter adjustment. This time intervall was choosen due to the best available data and the fact that this period represents vegetation conditions of a partly grown spruce forest. This first model application gave very close results for both HRU delineations. The model using 17 HRU and accounting for a higher level of basin heterogeneity simulated a slightly closer hydrograph to the observed data. According to these first model runs the following changes in the model will be made for the simulation runs over the time period from 1959 till 1996: (i) in order to simulate the change in vegetation cover the used evapotranspiration algorithm after Jensen & Haise (1963) will be replaced by a vegetation sensitive algorithm; (ii) due to over 150 foggy days a year in the study area an algorithm to simulate fogginess will be integrated into the PRMS/MMS modeling system: and (iii) in order to simulate the vegetation conditions of an upgrowing forest variable parameter files must be read by the system during run time.

## 4 OUTLOOK

The further research will mainly focus on two topics. First to simulate the dynamic of the vegetation change a direct adoption of vegetation parameters such as cover density and LAI must be directly supplied by a data base during the runtime of the model. Secondly parameter sets have to be defined to allow the application of the model to headwater catchments in the Thuringian Forest were much less data is available.

## 5 ACKNOWLEDGEMENT

The author is pleased to acknowledge the cooperation with Thüringer Ministry of Agriculture, Natural Conservation and Environment (TMNLU), the Environmental State Department of Thüringen (TLU) and the U.S.-Geological Survey, Denver, USA for the supply of the model and the model data.

## 6 REFERENCES

Anderson, M. G. & Burt; T.P.; *Process Studies in Hill-slope Hydrology*. Wiley, Chichester, U.K.; 1990.

Flügel, W.-A., Delineating Hydrological Response Units by Geographical Information System analyses for regional hydrological Modelling using PRMS/MMS in the drainage basin of the river Bröl, Germany. *Hydrological Processes, Vol. 9*, 423-436, 1995.

Haan, C.T., Johnson, H.P., Brakensiek, D.L.; *Hydrologic Modeling of Small Watersheds*. American Society of Agricultural Engineers, Michigan,

## CONCLUSIONS AND RECOMMENDATIONS

The simple genetic algorithm (GA) method has been modified through;

- a finetuning strategy involving automatic search range reduction and creep mutation of the elitist parameter set;
- a hillclimbing strategy consisting of automatic search range shift to the promising regions of search; and
- the use of independent subpopulation searches coupled with shuffling.

The modified GA effectively locates the global optima of the three test problems at varying levels of efficiency while the simple GA performs poorly with all three. It seems that the modified GA can be considered effective but not always efficient. Further tests would be needed to reveal more fully the capabilities and the limitations of the modified GA.

## ACKNOWLEDGMENTS

The authors express sincere thanks to Professors Soroosh Sorooshian and Vijai Gupta of the University of Arizona, USA and Dr. Qingyun Duan of NWS/NOAA, USA for providing software and data for the SIXPAR rainfall-runoff model.

## REFERENCES

Ambroise, B., Freer, J., and Beven, K., Application of a generalized TOPMODEL to the small Ringelbach catchment, Vosges, France, *Water Resour. Res.*, 32(7), 2147-2159, 1996.

Bates, B. C., Calibration of the SFB model using a Simulated Annealing Approach, *Proc. Int. Hydrol. and Water Resour. Symp.*, Adelaide, Vol.3, 1-6, 1994.

Beven, K. J., and Kirkby, M. J., A physically Based, Variable Contributing Area Model of Basin Hydrology, *Hydrol. Sciences, 24(1)*, 43-69, 1979.

Cohoon, J. P., Hegde, S. U., Martin, W. N., Richards, D. S., Distributed Genetic Algorithm for the Floorplan Design Problem, *IEEE. Trans. on Computer-Aided Design*, 10(4), 1991.

Donne, M. S., Tilley, D. G., and Richard's, W., The use of Multi-objective Parallel Genetic Algorithms to aid Fluid Power System Design, *Proc., Inst. Mech. Engrs.* 209, 53-61, 1995.

Duan, Q., Sorooshian, S., and Gupta, V., Effective and Efficient Global Optimization for Conceptual Rainfall-Runoff Models, *Water Resour. Res., 28(4)*, 1015-1031, 1992.

Duan, Q. Y., Gupta, V. K., and Sorooshian, S., Shuffled Complex Evolution for Effective and Efficient Global Minimization, *J. Optim. Theory and Appl.*, 76(3), 501-521, 1993.

GALESIA, First Int. Conf. on Genetic Algorithms in Engineering Systems: Innovations and Applications, Sheffield, UK, 1995.

Goldberg, D. E., *Genetic Algorithms in Search, Optimization and Machine Learning*, Addison Wesley, 1989.

Grayson, R. B., and Chiew, F. H. S., An Approach to Model Selection, *Proc. Int. Hydrol. and Water Resour. Symp.*, Adelaide, Vol.1, 507-512, 1994.

Holland, J. H., *Adaptation in Natural and Artificial Systems*, Univ. of Mich. Press, Arbor, 1975.

Hornberger, G. M., Beven, B. J., Cosby, B. J., and Sappington, D. E., Shenandoah Watershed Study: Calibration of a Topography-Based, Variable Contributing Area Hydrological Model to a Small Forested Catchment, *Water Resour. Res.*, 21(12), 1841-1850, 1985.

Johnston, P. R., and Pilgrim, D. H., Parameter Optimization for Watershed Models, *Water Resour. Res., 12(3)*, 477-486, 1976.

Kuczera, G., Efficient subspace probabilistic parameter Optimization for catchment models, *Water Resour. Res.*, 33(1), 177-185, 1997.

Mahfoud, S. W., Nitching methods for Genetic Algorithms, *IliGAL Report No. 95001*, Univ. of Illinios, 1995.

Mühlenbein, H., Schomisch, M., and Born, J., The Parallel Genetic Algorithm as Function Optimizer, *Parallel Computing*, 17, 619-632, 1991.

Ndiritu, J. G., and Daniell, T. M., Time-domain tuned rainfall-runoff models optimized using genetic algorithms, in Zannetti, P., and Brebbia, C. A., (Eds.), *Proc., Int"l. Conf. on Dev. and appl. of Computer Techniques to Env. studies*, Comp. Mech. Publ., Southampton, Boston , 268-275. 1996.

Nelder, J. A., and Mead, R., A Simplex method for function minimization, *Comput. J.*, 7(4), 308-313, 1965.

O'Connell, P. E., and Todini, E., Modelling of rainfall, flow and mass transport in hydrological systems: an overview, *J. Hydrol.* 175(1996), 3-16.

Pinter, J. D., Global Optimization in Action, Continuous and Lipschitz Optimization: Algorithms, Implementations and Applications, Kluwer Acad., Netherlands, 1996.

Powell, M. J. D., An Efficient Method for Finding the Minimum of a Function of Several Variables Without Calculating Derivatives, *Comput. J.*, 7, 155-162, 1964.

Sorooshian, S., Duan, Q., and Gupta, V. K., Calibration of Rainfall-Runoff Models: Application of Global Optimization to the Sacramento Soil Moisture Accounting Model, *Water Resour. Res., 29(4)*, 1185-1194, 1993.

Tanakamaru, H., and Burges, S. J., Application of Global Optimization to Parameter Estimation of the TANK Model, *Proc. Int. Conf. on Water Resour. and Environ. Res.*, Kyoto, Japan, Vol. 2, 39-46, 1996.

Tomassini, M., The Parallel Genetic Cellular Automata: Application to Global Function Optimization, in Albrecht, R. F., Reeves, C. R., and Steele, N. C., (Eds.), *Artificial Neural Nets and Genetic Algorithms*, Springer-Verlag, New York, 385-391, 1993.

Törn, A., and Zilinskas, A., *Global Optimization*, Lecture Notes in Computer Science 350, Springer-Verlag, Germany, 1989.

Wang, Q. J., Chiew, F. H. S., and McMahon, T. A., Calibration of Environmental models by genetic algorithms, *Proc., MODSIM 95, Int. Congress on Modell. and Simul.*, Modell. and Simul. Soc. of Aust., Newcastle, Vol. 3, 185-190, 1995.

Wheater, H. S., Jakeman, A. J., and Beven, K. J., Progress and Directions in Rainfall-Runoff Modelling, in Jakeman, A. J., Beck, M. B., and McAleer, M. J., (Eds.), *Modelling Change in Environmental Systems*, John Wiley & Sons, England, 1993.