Regional modelling of the hydrological impact of afforestation in a semi-arid headwater catchment in South Africa using the HRU-approach

Wolfgang-Albert Flügel & Helmut Staudenrausch
Geographisches Institut, Universität Jena
Löbdergraben 32, D-07743 Jena, Germany
Tel.: +49 - 3641 - 632 775; FAX +49 - 3641 632 727
e-mail: c5wafl@geogr.uni-jena.de
h.staudenrausch@geogr.uni-jena.de

Abstract The concept of **Hydrological Response Units (HRU's)** and their delineation by GIS-analyses was applied to the semi-arid upland Ntabamhlope catchment in the foreland of the Drakensberg mountains, Kwazulu-Natal, South Africa to model the hydrological impact of afforestation to the water yield of the catchment. HRUs are designed as object oriented model entities appropriate for upscaling and downscaling required in regional hydrological modelling. For the modelling exercise the MMS/PRMS model was adopted and HRUs were delineated by GIS overlay and reclassification analysis from a DEM (25m x 25m grid size) by classifying pedo-topo-geological associations and four dominant land use classes. The model parameterization was carried out in such a way that rainfall input not intercepted and consumed by evapotranspiration from the HRU's was routed to surface runoff respectively to a common conceptual subsurface storage. The latter was drained by interflow towards the shallow ground-water aquifer in the valley floors which in turn supplies the groundwater base flow in the channel network. The model was then run on base of the HRU's, first using a ten-years daily data time series (1977-1986). After large areas of the study catchment have been afforested with eucalypts, a second time period (three years daily time series, 1992-1995) was used to assess the concept's and model's capability and sensitivity to simulate such a landuse change. Future research activities will concentrate on establishing a hydrodynamical linkage between the sub-areas of each HRU by GIS means and on integrating remote sensing and GIS with an improved object-oriented model design.

1. INTRODUCTION

During the last decades hydrologists have focused their attention on the processes comprising a river basin's hydrological dynamics and runoff generation (HEWLETT & HIBBERT, 1967). The latter is controlled by various physiographic basin characteristics, such as precipitation, topography, soils, geology and land use which are heterogeneously distributed within the basin. They are also controlling infiltration, surface runoff and evapotranspiration, (ANDERSON & BURT, 1979; BEVEN & KIRKBY, 1979), and therefore they are subject for regional hydrological modelling (Beven et. al., 1988). In mountainous basins interflow in the hillslopes is of paramount importance for groundwater recharge and the generation of river runoff (ANDERSON & BURT, 1990; BINLEY & BEVEN, 1992; FLÜGEL, 1979, 1993; KIRKBY, 1978). The drainage basin therefore must be seen as a heterogeneous assembly of distributed entities having specific physiographic properties and precipitation input, each contributing differently to the basin's hydrological cycle and discharge output.

Models have to account for this heterogeneity if they claim to simulate the physical processes realistically. They therefore have to use physical laws or established empirical relationships from field studies (FLÜGEL, 1979), and must be modularily structured to account for module development for various hydrological dynamics in different climatic environments.

The PRMS/MMS model developed by the USGS (LEAVESLEY et al., 1983 & 1996) used in this study fulfills these two conditions. Recent research work also includes the techniques of GIS into hydrological modelling (MOORE, 1993; MAIDMENT, 1991) providing a set of tools for modelling heterogeneous structured drainage basins (FLÜGEL & LÜLLWITZ, 1993).

1.2 Objectives

The objectives of this study, which is part of a long term sytems analysis of the headwater catchments in the Drakenberg foothill region, basin were four-folded: (i) To further develop the concept of HRU's using the test basin of the Little Bushmans River in the Ntabamhlope region; (ii) present the method of GIS analysis to delineate HRU's of the Little Bushmans River in the Ntabamhlope region; (ii) present the method of GIS analysis to delineate HRU's based on the hydrological systems analysis; (iii) use the HRU's in PRMS/MMS to simulate the hydrology of the Ntabamhlope basin for; and (iv) identify further research needs to improve the modelling strategy presented.

1.3 Basin heterogeneity and HRU concept

Understanding the processes interacting within the Soil-Vegetation-Atmosphere (SVAT) interface is of paramount importance, and a systems approach is essential if the hydrological dynamics of heterogeneously structured drainage basins should be analyzed and modelled. Evapotranspiration, infiltration, surface runoff, interflow, groundwater recharge and runoff generation of the entire river basin are controlled by the SVAT-interface.

Fig. 1 is showing a "layer model" of a basin segment, and the interlinked water fluxes active within its topography. In terms of topography, soils, geology and land use the three-dimensional physiographic heterogeneity can be grouped together into different associations.

Topography, soil types and geology are associated in soil catenas due to processes of weathering and erosion, and form pedo-topo-geological association. As a result, a gley soil will be found at the valley floor with shallow groundwater, but rarely on the plains, and certainly not on the slopes. General land use classes are agriculture, grassland, forest and impervious areas. They also show interdependencies with the soil catenas as agriculture prefers fertile, deep developed soils in the valley floor and on gentle hills, while grassland and forests are restricted to shallow, less productive soils on the slopes and on the plains.

Fig. 1 clearly shows that each land-use class is located on a specific pedo-topo-geological association forming a unique entity in the basin. The basic assumption of the HRU-concept is, that each of these entities also has a unique hydrological dynamics due to their unique land-use management and their common physical properties of the underlying pedo-topo-geological association. They are then defined as Hydrological Response Units:

"Hydrological Response Units are heterogeneously distributed modelling entities with common land use and pedo-topo-geological associations controlling their unique hydrological dynamics".

This definition implies for each HRU, that the variation of the hydrological dynamics within it is negligible if compared with the difference to a neighboring HRU.

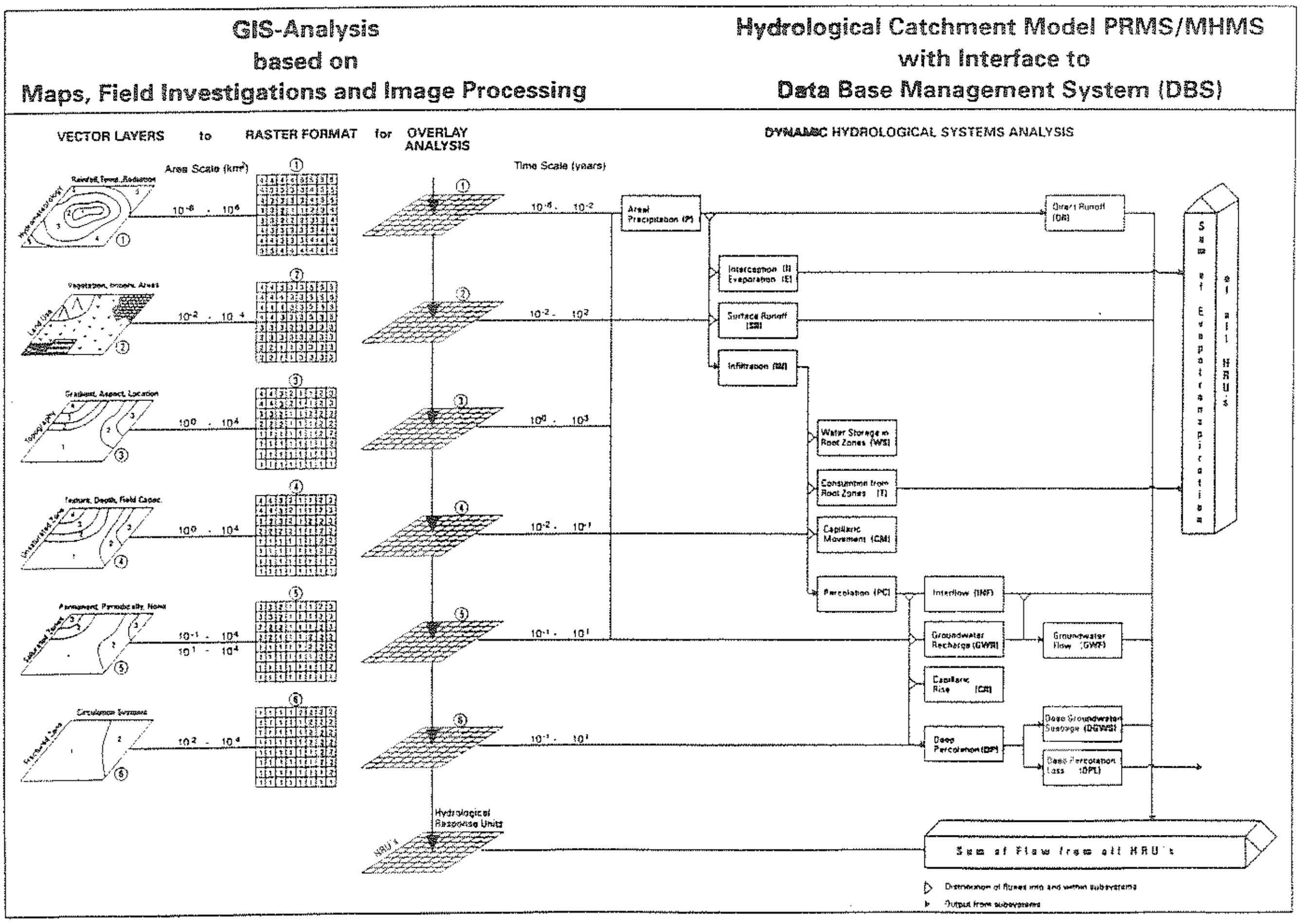

Fig. 1 Schematic layer presentation of basin subsystem storages and their interlinked water fluxes with various scales, conceptually connected to the distributed hydrological river basin model MMS/PRMS.

1.4 The study area

The study area Ntabamhlope ($A = 34.7$ km²) is situated approximately 200 km north-east of Durban, at 29°02'/29°33' Lat/Lon, in the province of Kwazulu-Natal in South Africa. It is part of a plateau above the DeHoek amphitheatre, in the region of the Little Berg, the foothills of the great escarpment of the Drakensberg mountains. The studied catchment itself is dominated by a large wetland ($A = 2.2$ km²) at the outlet.

Geologically, it consists of alternating sandstones and mudstones/shales belonging to the Beaufort Group of the Karoo Supergroup, laid down 300-600 m thick during late Permian to mid-Triassic times (SMITHERS & SCHULZE 1994). The soils of the Ntabamhlope area follow typical toposequences with little variation in their properties. Only in the valley floor a firm gley, differing fundamentally from the other soils of the region, has developed. On the slopes and the highland parts, red and yellow apedal loamy to sandy soils (Huttons, Clovellys; H&C in Tab.2) with high infiltration rates and rapid subsoil permeability are found. They show a good correlation in depth with the slope gradients, i.e. the steeper the slope, the shallower are the soil profiles (VAN DER EYK 1968).

The current landuse (own survey Jan. 1995) consists of mainly rangeland (59 %), used as pasture or meadow, and eucalypt stands (33 %) (*Eucalyptus nitens*, *Eucalyptus macarthurii*). Little pine stands as well as bush and mixed forests are almost negligible. The rest is cultivated with maize (2 %) and uncultivated wetland (6 %). In the years 1989/90 a large afforestation took place, so the area covered with forest doubled.

	before 1989		after 1990	
landuse	**km²**	**%**	**km²**	**%**
wetland	2.21	6.39	2.21	6,39
rangeland	25.9	74,9	20.4	58,9
forest	5.63	16,3	11.3	32,7
agriculture	0.84	2,41	0.71	2,01

Tab.1: landuse distribution in Ntabamhlope

The climate of the study area shows typical summer rain, semi-arid, subtropic characteristics with mean annual precipitation of ~1000 mm, falling almost entirely from October to April, mainly as storms. The mean monthly temperatures are, due to the high elevation of 1440 - 1830 m aSL moderate. (19°C in January to 7°C in June), but are accompanied by very high amounts of solar radiation.

Both climate and physiographic parameters drive the hydrological dynamics of the region. The runoff shows a typical semi-arid hydrograph, although the wetland situated above the outlet of the catchment has a certain equalizing impact on the runoff characteristics. A High rate of evapotranspiration is also a critical parameter for the hydrology of this region, reflecting the high input of solar radiation and other factors, such as wind, temperature and vegetation. The eucalypts have an enormous water consumption, proven by the afforestion in 1989/90, which caused a severe runoff reduction (SMITHERS & SCHULZE 1994).

2. HYDROLOGICAL SYSTEMS ANALYSIS

The drainage basin was intensively studied in various field campaigns and, additionally, the hydro-meteorological database was analyzed. From these studies the hydrological dynamics of the basin can be described as follows: (i) Surface runoff occurs only on the rangeland hillslopes during extreme rainfall events with high intensities; (ii) rainfall is intercepted by the forest and grassland vegetation, and the soil infiltration capacity can often account for the throughfall; (iii) the infiltrating water is stored in the pore volume of the unsaturated root zone for consumption by evapotranspiration; (iii) if field capacity is exceeded, water percolates further downwards generating lateral interflow; (iv) if coarse pores (earthworms, former root channels) are frequent, this slower percolation process is enhanced by the fast downwards flow of water from the surface towards this zone; (v) groundwater is restricted to the valley floors and is recharged by percolation from the unsaturated zone above, but the majority of its recharge is received by interflow from the adjacent slopes; (vi) wetlands on the moulded valley floors are buffering surface runoff and interflow inflowing from the adjacent slopes and causing a lag between rainfall events and corresponding hydrograph peaks.

2.1 GIS analysis, HRU delineation and linkage to the PRMS model

A comprehensive GIS database was built up by digitizing maps of soil types (VAN DER EYK 1968) and land use (from orthophoto maps made in 1967), as well as the current landuse, mapped during a survey in 1995, and by importing a DEM into the GIS. The DEM was used to identify catchment boundaries, flowdirection and to automatically delineate the streamnet, using the specific flowaccumulation of each cell location of the DEM and thresholding it to define all cells belonging to the streamnet. Other hydrological and morphometrical parameters have been calculated for further systems understanding.

To take into account for the unaccuracy of the digitized soils map, a new soils layer was created by accomplishing digital terrain analysis in conjunction with hydrological analysis and landcover information. In detail, four soil distribution areas according to the four soil types in the original map could be identified following certain rules concerning slope gradient, distance to streamnet and wetland vegetation. Apart from the gley area in the valley floor, all other soil areas could then easily be associated to slope classes.

In order to compare the former landuse before 1990 and the current afforested landuse after 1990, both maps were taken into the GIS database.

The HRU's were delineated by GIS-analyses as follows: (i) slopes and aspect were derived from the DEM; (ii) topography soils and geology were grouped into the four different pedo-topo-geological associations of plains (0 - 10% slope and deep soils, (h&c. d)), slope 1 (10 - 20% and intermediate soill depths, (h&c. i)), slope 2 (> 20% and shallow soils, (h&c. s)), the valley floor (> 0% and gley soil); (iii) areal mean daily precipitation was calculated from Thiessen polygons and was applied to all HRU's weighted by their size of area; (iv) three land use classes of forest (mainly eucalypt stands), rangeland, and agriculture areas were classified. During the GIS overlay analysis, generated subclasses with small areas were merged with similar larger classes based on the insight gained by the hydrological systems analysis. This work sequence was performed twice to obtain two model bases, one for either simulation period. In this manner, a versatile and flexible database can be created to detect changes in time as well as investigate multiple scenarios. Using the entire GIS data base, 22 HRU's in total were delineated for each period:

HRU	landuse	slope grad.	aspect	⌀ elevation [ft]	⌀ slope [%]	soil	area [acre]
1	Wetland	0-3 %	all	4790.86	1.675	gley	896.213
2	Grassland	0-10 %	North	4940.33	5.501	h & c, d	948.604
3	Grassland	0-10 %	East/West	4962.30	6.139	h & c, d	558.638
4	Grassland	0-10 %	South	4990.66	6.282	h & c, d	538.671
5	Grassland	10-20 %	North	5123.91	14.381	h & c, i	553.498
6	Grassland	10-20 %	East/West	5049.18	14.333	h & c, i	502.347
7	Grassland	10-20 %	South	5014.10	14.429	h & c, i	626.637
8	Grassland	> 20 %	North	5210.61	27.429	h & c, s	246.85
9	Grassland	> 20 %	East/West	5109.79	30.075	h & c, s	305.411
10	Grassland	> 20 %	South	5092.04	29.000	h & c, s	419.323
11	Forest	0-10 %	North	4907.68	5.734	h & c, d	853.966
12	Forest	0-10 %	East/West	4898.77	6.387	h & c, d	390.66
13	Forest	0-10 %	South	4953.26	6.071	h & c, d	299.044
14	Forest	10-20 %	North	5017.38	14.080	h & c, i	453.916
15	Forest	10-20 %	East/West	4964.71	13.987	h & c, i	294.045
16	Forest	10-20 %	South	4973.73	13.865	h & c, i	150.235
17	Forest	> 20 %	North	5117.26	28.792	h & c, s	188.782
18	Forest	> 20 %	East/West	5056.35	29.561	h & c, s	136.892
19	Forest	> 20 %	South	5030.48	35.425	h & c, s	122.066
20	Agric.	> 0 %	North	4792.94	4.042	h & c, d	77.341
21	Agric.	> 0 %	East/West	4784.57	4.869	h & c, d	69.187
22	Agric.	> 0 %	South	4780.73	4.511	h & c, d	23.721

Tab.2: List of the 22 HRU's and their physical properties for the period after afforestation.

If linking the GIS analyses with the hydrological catchment model one must provide a conceptual interface between the data layers represented in the GIS database and the model modules simulating the different processes active within the various subsystems of the basin. This conceptual and systematic linkage is shown in Fig. 1 and can be done with the PRMS model incorporated into the MMS Modular Modelling System. The modular structure of MMS/PRMS guarantees that modules can be adapted or exchanged by other developpers to simulate the physical processes in a more appropriate way. As can be seen from Fig.1 each process of the hydrological dynamics is simulated on the level of the GIS data layer and summarized for each HRU thus providing a real world distributing modelling.

3. APPLICATION IN THE MMS/PRMS MODEL

After delineating the HRU's as base entities for modelling the catchment and deducing model relevant parameters from GIS analyses and field surveys, they could be transferred into MMS/PRMS. A first set of parameters was calibrated by adjusting the simulated hydrograph to the observed runoff of the year 1993. Subsequently, this setting was validated with observed time series from 1992 to 1994, showing a good conformity (Fig.2) with a correlation coefficient of 0.96 (1992) and 0.85 (1994). Also peaks are well modelled

(Tab.3, 1st block,. sim93). Slightly worse performance for 1994 can be explained by regaging the catchment during this time. The next step of validation was to apply the parameter setting to the years before the afforestation took place, i.e. 1976 to 1986. The goal was to evaluate the model's capability to reproduce the landuse change without recalibrating the parameters to a hydrograph from this time period. The only change in the model setup was to use the HRU distribution delineated with the old landuse. It turned out, that correlation and shape of the hydrograph still was satisfying, while the extrema as well as the overall mean were now modelled far to low (Tab.3, 2nd block, cols. sim93). Investigating the parameters' sensitivity to landuse changes, the algorithm calculating evapotranspiration after JENSEN & HAISE (1963) used in this study was found not be sensitive to the afforestation in this climate. The problem was, that then not enough water resided in the system, because the parameters for the evapotranspiration have been calibrated to the afforestated state of the area, however, not being able to reproduce landuse change-induced change of evapotranspiration.

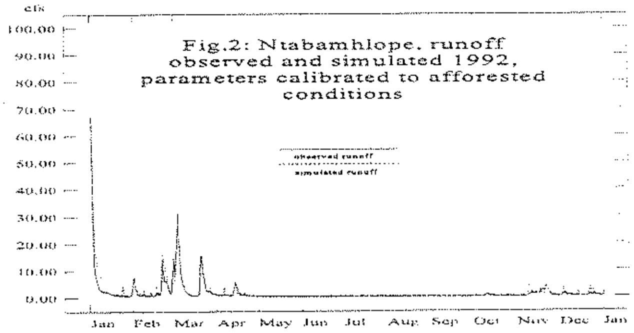
Fig.2: Ntabamhlope. runoff observed and simulated 1992, parameters calibrated to afforested conditions

	1992-1994			1992			1993			1994		
	obs	sim93	sim81	obs	sim93	sim81	obs	sim93	sim81	obs	sim93	sim81
min	0.01	0.05	0.04	0.15	0.09	0.05	0.13	0.14	0.07	0.01	0.06	0.04
max	120.7	136.2	271.3	67.0	65.86	91.25	120.7	136.2	271.3	49.65	48.47	97.25
⌀	2.641	2.778	7.738	1.62	1.87	4.325	4.65	4.69	13.08	2.66	2.02	5.79
s	7.50	9.01	19.35	4.72	4.97	9.01	10.4	14.36	29.35	5.88	5.16	11.64
r		0.886	0.881		0.963	0.933		0.950	0.922		0.853	0.836
	1976-86			1981			1982			1983		
	obs	sim81	sim93	obs	sim81	sim93	obs	sim81	sim93	obs	sim81	sim93
min	0	0.003	0.009	0.05	0.10	0.177	0	0.06	0.03	0	0.003	0.01
max	306.2	342.1	219.7	306.3	342.0	219.7	45.14	46.70	19.24	82.26	122.6	49.87
⌀	5.432	5.947	2.144	12.4	13.82	6.306	1.922	2.786	0.915	1.833	3.087	1.04
s	15.92	17.26	3.718	31.7	36.04	21.51	4.55	5.72	2.29	6.55	10.08	3.91
r		0.843	0.77		0.917	0.856		0.86	0.814		0.93	0.914

Key:
obs: observerv runoff [cfs]
sim93: simulated runoff using parametes calibrated to afforested landuse [cfs]
sim81: simulated runoff using parametes calibrated to non-afforested landuse [cfs]
min: minimum runoff; max: maximum runoff; ⌀: mean runoff; s: standard deviation
r: correlation coefficient beetween observed and simulated runoff

Tab.3: Statistics for the simulation of the period after afforestation, using two different parameter sets calibrated for the two different simualtion periods before and after afforestation.

To verify those results, a cross-check was performed, now calibrating a parameter set to the non-afforested conditions. First they were validated using the time series from 1976 to 1986, again showing good conformity between simulated and observed runoff (Tab.3, second block, cols. sim81). Then this setup was applied to the years 1992-1994, using the HRU distribution with the afforested landuse, but without changing parameters. Now, as expected, a heavy oversimuation of the runoff occured due to to much water in the system (Tab.3, first block, cols. sim81), while correlation and shape of the hydrograph still was satifying, just analogue to the cross-test, being the other way around.

The above explained modelling methodology shows the capability of MMS/PRMS to simulate the hydrolo-gical response of a semi-arid subtropic area in Africa. Also, the algorithm used to calculate evapotransiration wasp proven not to be sensitive to landuse changes, such as afforestation. If an improved evapotranspiration module within the same model concept and setup will be applied, then, however, a stable, comprehensible and flexible conceptual appraoch would be the result.

4. OUTLOOK

As results from this study as well as from many others applied to other climatic and geographic regions, two major further research tasks can be identified:

(i) Development of an open, flexible modelling system including a large model and algorithm library. This is the pre-condition to be able to create specific model setups for any modelling problem in an easy way. This modelling system should provide easy access to the library as well as open interfaces to database management systems and geographical information systems. Such an approach is currently being developped at the department of geoinformatics at University of Jena.

(ii) Implementation of a detailed networked topology between the splitted parts of the modelling entities, the HRU's. This will allow to apply area-based routing through the polygons as well as linear routing via streamnet. Particularly at large spatial scales and small time steps, routing becomes more and more important in hydrological modelling.

5. ACKNOWLEDGEMENTS

The authors are pleased to acknowledge the cooperation with Prof. Dr.R. Schulze, Dept. of Agric. Eng., Univ. of Natal, Sotuh Africa for supply of the time series data and map information.

6. REFERENCES

Anderson, M.G. & Burt, T.P., The role of topography in controlling throughflow generation. *Earth Surf. Processes, 3*, 331-344, 1978.

Anderson, M.G. & Burt, T.P. (Ed.), *Process Studies in Hillslope Hydrology*. Wiley, Chichester, U.K, 1990.

Beven, K.J. & Kirkby, M.J., A physically-based variable contribution area model of catchment hydrology. *Hydrol. Sci. Bull. 24*, 43-69, 1988.

Beven, K.J., Wood, E.F. & Murugesu, S., On hydrological heterogeneity-catchment morphology and catchment response. *J. Hydrol. 100*, 353-375, 1990.

Binley, A. & Beven, K., Three-dimensional modelling of hillslope hydrology. *Hydrol. Processes. 6*, 347-359, 1992.

Flügel, W.-A., Untersuchungen zum Problem des Interflow, *Heidelberger Geogr. Arb.,H. 56*, p.176, 1979.

Flügel, W.-A., Hierarchically Structured hydrological process studies to regionalize interflow in a loess covered catchment near Heidelberg, *IAHS-Publ. No. 212*, 215-223, 1993.

Flügel, W.-A. & Lüllwitz, TH., Using a distributed model with GIS for comparative hydrological modelling of micro- and mesoscale catchments in the USA and in Germany, *IAHS-Publ. 214*, 59-66, 1993.

JENSEN, M.E., HAISE, H.R., Estimating evapotranspiration from solar radiation. *Proceedings of the American Society of Civil Engineers, J. Irrig. and Drain., Vol. 89, No. IR4*, 15-41, 1963.

Kirkby, M.J., *Hillslope Hydrology*, Wiley, Chichester, U.K, 1978.

Leavesley, G.H., Lichty, B.M., Troutman, L.G., Saindon, L.G., Precipitation-Runoff Modeling System: User's Manual, *USGS Water-Resources Investigations Report 83-4238*, Denver, USA, 1983.

Leavesley, G.H., Restropo, P.J., Markstrom, S.L., Dixon, M., Stannard ,L.G., The Modular Modeling System (MMS): User's manual. *USGS Open-File Report 96-151*. Denver, USA, 1996.

Maidment, D.R., GIS and Hydrologic Modeling, *Proceedings of the First International Symposium/Workshop on GIS and Environmental Modeling, Sept. 15-19, 1991*, Boulder, USA, 1991.

Moore, I.D., Hydrologic Modelling and GIS, *2nd Int. Conf. on Integrating Geographic Information Systems and Environmental Modeling, Sept. 26-30, 1993*, Breckenridge, USA, 1993.

Smithers J.C., Schulze R.E., The Dehoek/Ntabamhlope hydrological research catchments. *Agricultural Catchments Research Unit report no. 42*. Pietermaritzburg, S.A., 1994.

Staudenrausch, H., Die Anwendung des HRU-Konzepts für die hydrologische Modellierung eines semiariden Einzugsgebiets in Südafrika. *In: Zbl. Geol. Paläont. Teil I, 1996 (7/8)*: xxx-xxx; Stuttgart, Germany, 1997. (in press)

Van Der Eyk, J.J., De Villiers, J.M., MacVicar, C.N. , *Soils of the Tugela basin*. Pietermaritzburg, S.A., 1968.