Regionalization in Hydrology (Proceedings of a conference held at Braunschweig, March 1997).
IAHS Publ. no. 254, 1999.

Remote sensing, hydrological analysis and hydrotopes

A. M. J. MEIJERINK, M. LUBCZYNSKI & P. WOLSKI
International Institute for Aerospace Survey and Earth Sciences (ITC), PO Box 6, 7500 AA Enschede, The Netherlands
e-mail: meijerink@itc.nl

Abstract Remotely sensed images are used to differentiate complex terrain mapping units, which are based on natural associations of geology, geomorphology and soils. Land cover, also derived by remote sensing, is added. Based on an understanding of the role of terrain characteristics, analysis of existing hydrological data and field observations, a conceptual, but comprehensive, hydrological model is formulated. In this manner, the effects of spatial variation of hydrological parameters can be taken into account even in data scarce regions. The procedure leads to the recognition of hydrotopes, which are complex units with a specific set of hydrological processes and therefore, a specific water balance. Depending on the nature of the terrain and the purpose of study, modelling approaches are developed which often deviate from routinely used models. A first example deals with the assessment of spatial recharge in a granitic area, which is used as an independent parameter for the calibration of a numerical groundwater model. The second example pertains to a permeable region, where local groundwater flow systems are modelled by quasi-linear tank models.

INTRODUCTION

The distributed modelling of hydrological interactions by a numerical simulation model soon faces a problem, known as "parameter estimation crises", as is discussed in depth by Beven (1996). Particularly in areas with constraints on data availability, the question arises of how the hydrology of such areas can be better understood. In this contribution, attention is drawn to the qualitative information contained in remotely sensed images and to the follow-up by using conceptual models.

Technological advances make it possible to combine information from various platforms, such as stereo aerial photographs, multi-spectral, micro-wave and thermal images, through image fusion, and links to existing thematic data through GIS operations. It is therefore possible to use information on the spatial variation of terrain factors which influence hydrology.

However, the interactions of surface and subsurface hydrological processes cannot be observed directly on the images. In general, the conceptualization of the hydrological processes by semi-qualitative hydrological reasoning, is based on the analytical interpretation of the stereo model and other images. Use is made of the natural associations of geology, geomorphology and soils, and often land cover. Segmentation of the terrain is done by differentiation of complex terrain mapping units (TMUs). After that, an attempt is made to describe, and where possible quantify, the fluxes within each unit. In this process aggregation or disaggregation of the TMUs may be desirable so as to transform them into what may be termed "hydrotopes".

TERRAIN MAPPING UNITS

Many years of research in geomorphological mapping strongly suggests that pragmatic terrain classifications have to be "open ended", non-hierarchical, and adjustable to scale and purpose. The units are often based on the geology, which generally governs the conditions near the surface. Verstappen & van Zuidam (1991) developed a flexible but systematic method for the delineation and classification of terrain units based on geomorphology and geology.

The degree of internal complexity of the TMUs depends, at a given scale of investigation, on the complexity of the terrain to factors such as lithological variations within a formation, catenary successions, drainage network characteristics and so on. Subunits, also to be determined from the images, can be differentiated but not necessarily mapped. The subunit can pertain to catenary elements or other geomorphological elements that influence hydrological processes. These subunits are often too small to be mapped at medium or small cartographic scales. However, they can be sampled and their role can be included in the conceptual modelling. Land cover types that play an important role in the hydrological processes are added to the terrain units. Thus the TMUs are not derived by overlaying in GIS mode. They are interpreted as the natural associations of geology, geomorphology and soils on the images.

HYDROTOPES

A hydrotope may be described as a TMU with hydrological information added. The advantage of working with hydrotopes is that the effects of spatial variations, as observed in the terrain, are included in the hydrological analysis, even if data are scarce. Therefore, in our experience, conceptual modelling is usually an appropriate way of quantification or "adding hydrological information".

The nature of the dominant hydrological process influences the descriptions of hydrotopes. It makes sense to assess first the relative importance of surface runoff against groundwater flow. The peak runoff coefficient on permeable terrain can be about 15 times lower than that on impermeable terrain (Halasi Kun, 1974). Peak flow estimates using the slope area method within the TMUs usually show important differences. For smaller catchments the differences between the peak runoff from terrain of contrasting permeability can even be larger (Meijerink, 1985).

In impermeable, steep terrain, where direct runoff and erosion are dominant, attention will be focused on the differentiation of TMUs whose attributes influence the generation of fast runoff. If groundwater flow is important, it is useful, first of all to study local and subregional groundwater flow systems in terms of recharge and discharge areas (Engelen & Kloosterman, 1996). Attempts to model the groundwater flow system along selected cross sections, often help in the hydrological characterization of TMUs and the estimate of groundwater exchange within and between TMUs.

In groundwater recharge areas spatial variation of the net recharge is of interest. Groundwater discharge areas can be inferred or observed on images, as discussed by Meijerink (1996). Apart from evaporative losses, such areas may generate saturation overland flow seasonally.

Besides peak flow estimates, understanding the nature of hydrological processes and flow systems in each TMU is helped by other field hydrological observations, such as base flow measurements, water quality determinations, enquiries as to the fluctuations of the groundwater level in wells, and so on.

With the spatial information contained in the images and the conceptualization of the hydrological processes in the TMUs, it can be decided what further quantification or modelling is needed. In the following sections two examples are discussed to illustrate how the above concepts are put in to practice in two areas of different permeability. The reasons for the various kinds of modelling are discussed.

APPLICATION TO A HARD ROCK AREA

The first example relates to an area in Spain, about 40 km west of Salamanca. The major objective of the hydrological study was to assess the groundwater resources. The NDVI SPOT image at Fig. 1 shows differentiation of the terrain into TMUs. This section discusses how the surface feature information shown on images is used for the units of so-called "hard rocks"—*in casu*, granite, gneiss and quartzite dyke—in a subcatchment of the Rio Tormes catchment in the west of Spain.

Groundwater resources are best quantified through numerical groundwater modelling. Most of the computer modelling codes used for this purpose are developed

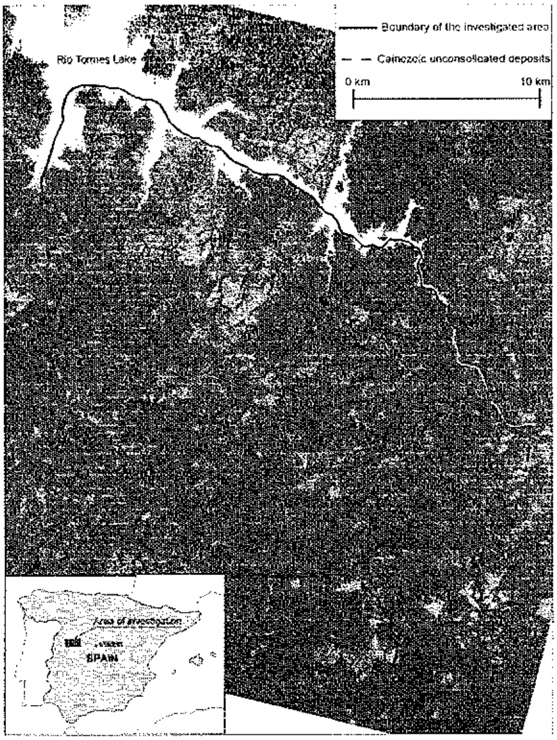


Fig. 1 SPOT NDVI image showing the dominance of the granitic TMU in the study area. Other units are composed of Cainozoic unconsolidated deposits.

for porous media. However, in fractured hard rock terrain the hydrotopes are characterized by anisotropy, heterogeneity and non-continuity of the flow system. Therefore, scale problems are prominent when dealing with the transmissivity. At very large cartographic scales, the model elements can have extremely low transmissivity if solid granite blocks are encountered, but adjoining elements can have high transmissivity where deep fractures and associated weathering occur. Therefore, very often in the modelling procedure a distinct increase of effective transmissivity with increasing observation scale is reported (Sanchez-Vila *et al.*, 1996). Thus, the equivalent porous media models give a poor representation of the hydrological system if applied in a routine manner, in which the transmissivity is regarded as an independent variable and recharge is treated as a calibration model parameter (dependent variable). To alleviate the problem, another approach is introduced in this study. Spatial recharge, rather than transmissivity, is used as an independent variable for model calibration. The cells of the model are considered as units (MODFLOW finite difference method solution) which receive, store and transmit the net recharge.

In order to quantify the recharge, first the relative recharge approach was assessed by a GIS procedure using information contained in remote sensing images. The four factors (attributes) selected for the relative recharge mapping were: fracture density, drainage density, land cover and lithology (Fig. 2). Each attribute has been divided into classes, which have been mapped using images and where necessary, field work. A conceptual model was developed to assess the weights given to each of the classes according to their estimated contribution to the recharge. The maps showing the four attribute classes have been aggregated by using two-dimensional tables. The result is a map with relative recharge classes where the digital number represents a pixel zone with certain recharge value (Fig. 3).

Validation of the relative recharge estimates was provided by using the results of a simple soil water balance calculation, analysis of well hydrographs, infiltration tests,

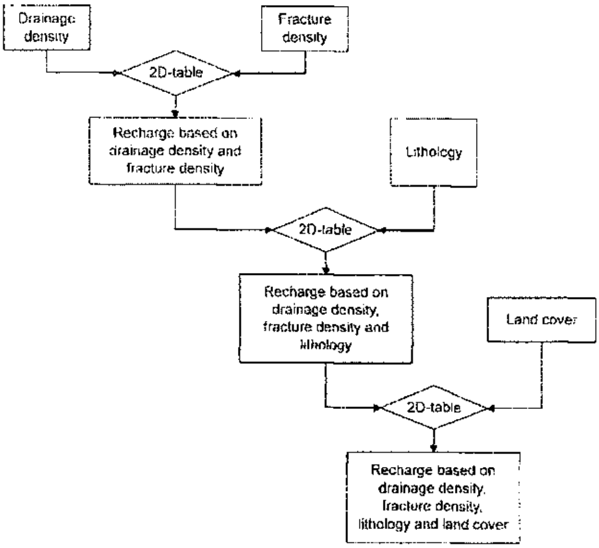


Fig. 2 Flowchart of the combination (crossing) of GIS attributes for the recharge estimation.

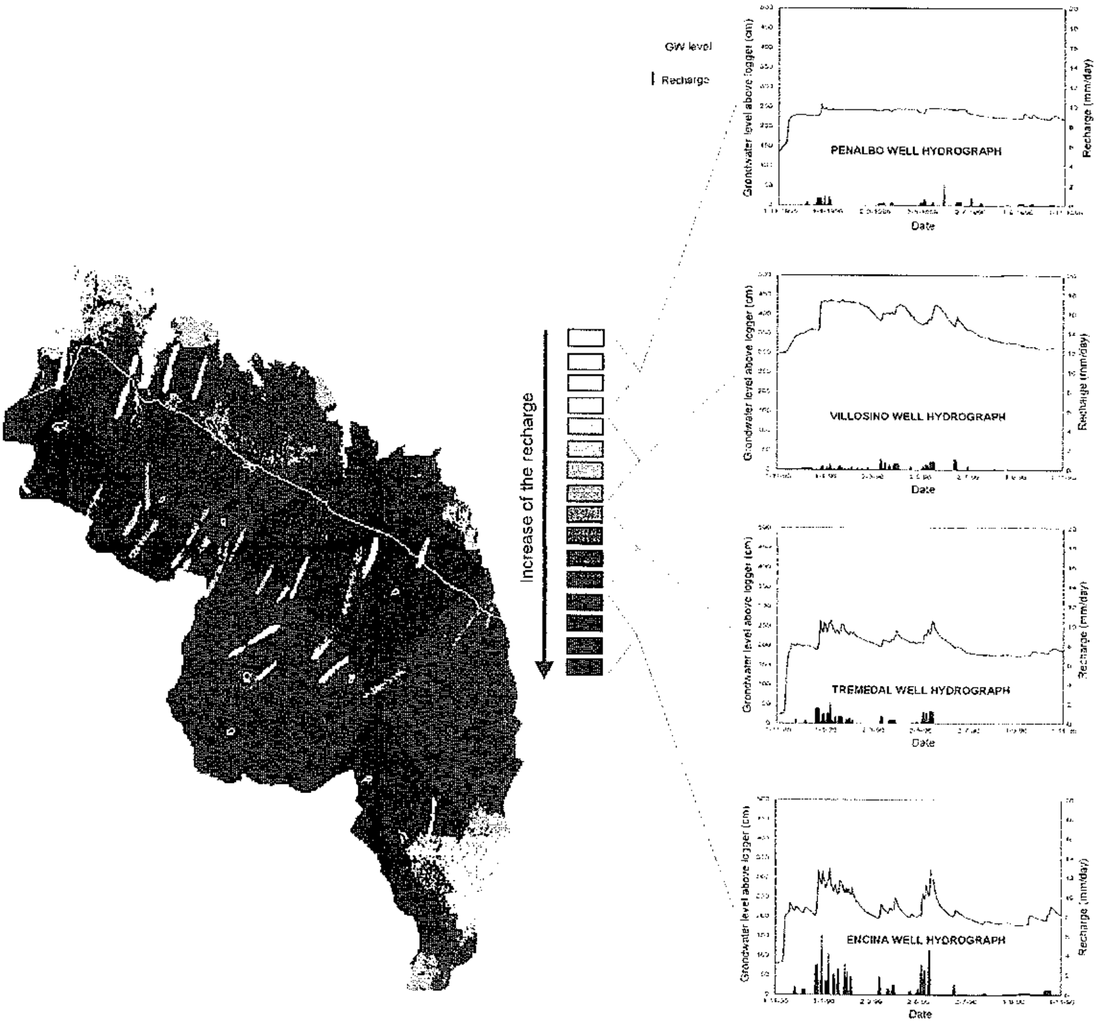


Fig. 3 Relative recharge map given in classes, referenced to wells whose hydrographs have been used for the calculation of recharge.

chloride sampling and base flow observations. In the final analysis the well hydrograph method has been used as the chief data source for the verification of the relative recharge map, because:

(a) Water levels in wells respond to the recharge, and transient conditions can be studied. Inexpensive and reliable electronic water level recorders (loggers) can be installed with ease.

(b) Although well observations are made at a single point, the water levels reflect the hydrological responses within subunits, such as upper interfluves with outcrops, slope units with weathering, valley bottoms, and so on.

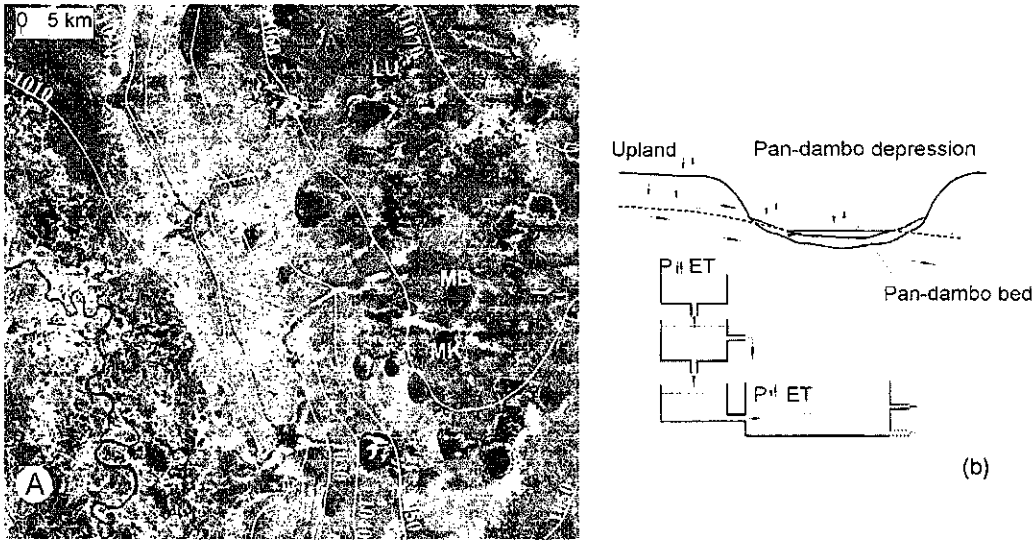
(c) Well observations can be made in selected places, whereas base flow depends on the presence of streams.

In the study area, ten loggers have been installed in various recharge units, selected on the basis of the relative recharge map. Four typical groundwater table responses have been differentiated with reference to four different aggregated recharge zones. Based on depth to groundwater, precipitation data and a laboratory based estimate of specific yield, four transient quantitative recharge records were derived with respect to relevant recharge zones. When there was disagreement between the relative recharge map and the recharge obtained from the well data, the conceptual model was adjusted and the GIS processing repeated till the map fitted the observations, at least for those subunits where well data was available. In other units, chloride data were used as a support for the recharge. The base flow data were used to verify the recharge integrated over the catchment.

For the last step, the spatially distributed recharge from the software GIS ILWIS was integrated into the MODFLOW numerical environment where the model was calibrated with a very efficient automatic inverse procedure (Lubczynski, 1997).

APPLICATION TO A PERMEABLE AREA

The region of study is the Western Province of Zambia. Based upon colour images of NOAA AVHRR and Landsat Thematic Mapper (not shown here), several TMUs could be differentiated in the region from rock type, geomorphology and vegetation cover, which partly reflects climatic gradients. Out of these factors, two main TMUs were identified in the study region: the large interfluve and the flood plains of the Zambezi and Lui Rivers. In Fig. 4(a) parts of the Zambezi flood plain TMU and the interfluve TMU are depicted, with boundaries between the units marked by light tones (high vegetation activity at seepage zone) more or less along the 1020 m a.s.l. isoline.



MK- Mukangu MB - MumbwanaLU - Lutende
Mbalili and Liambu - out of the image window (a)

Fig. 4 (a) MSS NDVI image of the area with groundwater contour lines and position of analysed pan-dambos indicated; (b) scheme of the hydrology of a pan-dambo and conceptual model used.

Because of high infiltration and permeability (the area is covered by a 80–130 m thick blanket of multi-origin sandy deposits of the Kalahari Formation), the hydrology is dominated by groundwater flow.

The objective of the study was to study hydrotopes. As mentioned earlier, this requires the understanding and quantification of the hydrological processes by taking the information contained in the TMUs as a starting point. The conceptual model developed showed that local groundwater flow systems were superimposed on sub-regional, or possibly even regional flow systems in the Kalahari Formation. Two-dimensional modelling along cross sections revealed that no regional flow system exists. Each interfluve has its own sub-regional flow system draining into the river valleys.

The subunits on the interfluves correspond to groundwater discharge areas in the dambos (local name of seasonally inundated depressions) and recharge areas around them. No signs of surface runoff has been observed in the recharge areas. Dambos are shown as dark, more or less circular areas on the NDVI image of Fig. 4(a). Their origin is attributed to silica karst and because they have no outlet for surface water they are termed pan-dambos.

The pan-dambo water regime, due to the semi-permeable nature of the bottom layer, is dependent on the position of the bottom in relation to the subregional groundwater table. The paucity of data prevented the use of a distributed groundwater model to study the local flow systems. It was decided to augment the conceptual model by another model consisting of quasi-linear tanks and to use water level records in a few dambos as validation. After various simulations, it was found that a fairly simple configuration of tanks, shown in Fig. 4(b), can simulate the vertical recharge and the lateral flow into the dambo. The three tanks on the left-hand side represent the recharge areas. No lateral outlet is given to the upper tank. A lateral outlet of the medium tank is required to simulate a lateral flux at medium soil depth due to the presence of thin layers of reduced permeability in the sandy formation. The dambo receptor tank has two outlets. The upper one is active only during high water levels in the dambo. Vertical openings in the lower tanks are omitted, because the inflow of the regional groundwater flow below the tanks is assumed to be equal to the outflow. The equation governing the outflow from a single outlet of a tank is $q = q_o e^{-\alpha t}$, where α denotes the drainage factor of the outlet.

Daily rainfall and actual evaporation were used, the latter estimated with a simple empirical equation based on antecedent moisture conditions. The flux between the two lower tanks has been estimated independently by using the Darcy equation. Water levels in the model's lower tanks were set at absolute heights. The drainage factors for the "openings" have been calibrated by trial and error, using the water level data of a selected dambo. The results are shown in Fig. 5(a).

The model, with the same tank parameter values (except the sizes of recharge and discharge areas and initial conditions) was applied to the other dambos for which water level records existed. The results were informative, particularly when a poor fit between observed and simulated water levels was noted. The simulated water level for the dambo of Fig. 5(c) was too low during the peak flood of 1991, because the overflow from the adjoining upstream tank (Fig. 4(a) and 5(a)) was not considered in the model. When the model was applied to another dambo, the simulated water level was too high for certain periods, as is shown in Fig. 5(d). This is probably due to the

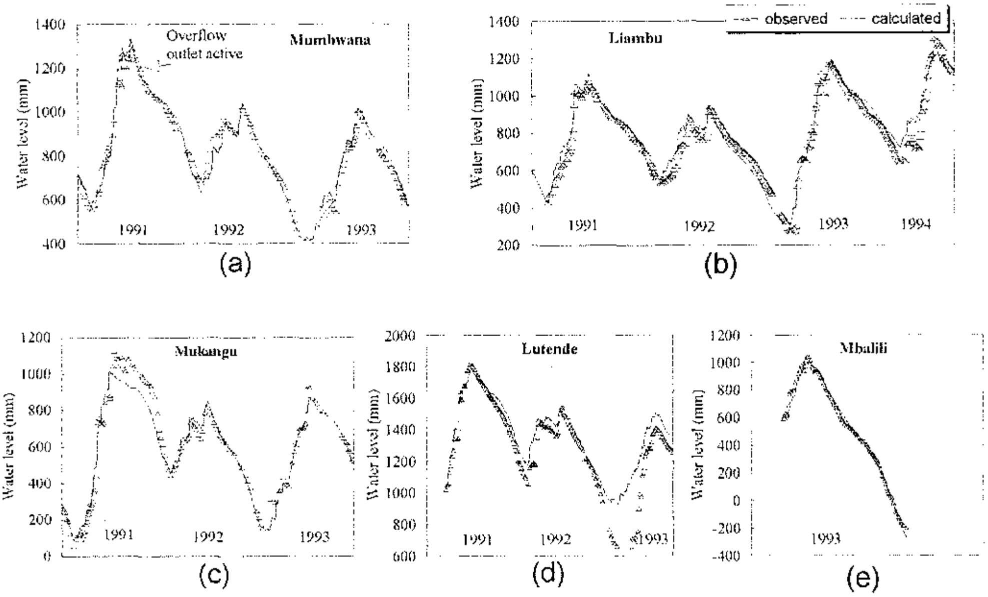


Fig. 5 The observed and calculated water levels for some pan-dambos.

loss of contact between the water in the dambo and the groundwater table which fell below the dambo bottom during the dry year of 1992.

In fact, the deviations supported the conceptual model, but additions have to be made to account for the effects of very dry or wet conditions. The otherwise good agreement between observed and simulated water levels in the dambos, confirms the hydrological uniformity of the local flow systems, superimposed on a subregional flow system. This tallies with the fact that no other hydrotopes can be observed on the imagery depicting the interfluve between the Lui and Zambezi rivers.

The next phase of the research will refine the scale at which hydrological processes can be studied by investigating the effects of vegetation on the spatial variation of the vertical fluxes of the upper tank. The surface energy balance method using thermal imagery will be used.

CONCLUSIONS

The regionalization of hydrology can be based on the complexity of the terrain. Spatial variations of terrain and cover factors can be mapped from remotely sensed images but not the hydrological processes. It is useful to formulate first a qualitative conceptual hydrological model, in order to direct the field observations and to decide on the modelling approaches.

After that, modelling results lead to the recognition of hydrotopes and a quantification of the processes.

In the hard rock region discussed, the assessment of the spatial recharge patterns, circumvented the difficulty of unknown spatial variations in transmissivity. The study in the permeable region showed that using a tank model, the local flow systems, as superimposed on a subregional one, could be described with good accuracy.

REFERENCES

Beven, K. J. (1996) A discussion of distributed hydrological modelling. In: *Distributed Hydrological Modelling* (ed. by M. B. Abbott & J. C. Refsgaard), 255–278. Water Science and Technology Library, Kluwer, Dordrecht, The Netherlands.

Engelen, G. B. & Kloosterman, F. H. (1996) *Hydrological Systems Analysis: Methods and Applications*. Kluwer, Dordrecht, The Netherlands.

Halasi Kun, G. (1974) Improvement of runoff records in smaller watersheds based on permeability of the geologic subsurface. In: *Design of Water Resources Projects with Inadequate Data* (Proc. Madrid Symp., June 1973), vol.1, 191–204. IAHS Publ. no. 108.

Lubczynski, M. (1997) Application of numerical flow modelling combined with remote sensing and GIS techniques for the quantification of regional groundwater resources in hard rock terrains. In: *Hard Rock Hydrosystems* (ed. by T. Pointet) (Proc. Symp. during Fifth IAHS Assembly, Rabat, April–May 1997), 151–157. IAHS Publ. no. 241.

Meijerink, A. M. J. (1985) Estimates of peak runoff from hilly terrain with varied lithology. *J. Hydrol.* 77, 227–236.

Meijerink, A. M. J. (1996) Remote sensing applications to hydrology: groundwater. *Hydrol. Sci. J.* **41**(4), 549–561.

Sanchez-Vila, X., Carrera, J. & Girardi, J. P. (1996) Scale effects in transmissivity. *J. Hydrol.* **183**, 1–22.

Verstappen, H. Th. & Van Zuidam, R. A. (1991) *The ITC System of Geomorphological Mapping*. ITC Publ. no. 10 (second edn), Enschede, The Netherlands.