The use of SAGA-GIS in an integrated meteorological/ hydrological model for the Mawddach river catchment, North Wales

Graham Hall, Roger Cratchley and Sarah Johnson
School of Agricultural and Forest Sciences,
University of Wales, Bangor

ABSTRACT

A process model is being developed for a mountain region of North Wales which regularly experiences destructive flood events. SAGA-GIS plays a central role in this model. A 50m gridded digital elevation model is loaded into SAGA, and the Kirkby wetness index calculated. Geology and land use maps have been prepared using Mapmaker software, then transferred to SAGA in Arc View shape file format. Output from SAGA is transferred in Arc Info grid format to a hillslope modelling program. By combining wetness index with geology/land use, a grid of hydrologically similar soil zones has been generated using the UK Centre for Ecology and Hydrology HOST classification scheme. Infiltration and run-off parameters can then be assigned from field evidence.

INTRODUCTION

Development of a flood prediction system is taking place for the mountainous Mawddach catchment in North Wales, where a flash flood event in July 2001 caused extensive damage to bridges, roads and buildings.

Headwaters of the river system flow from peat blanket bogs where field monitoring has identified significant water table variation during the year. The middle courses of the main tributaries flow through steep gorges, where reversals of river bed temperature profile indicate resurgence of groundwater during flood events. For these reasons it has been necessary to incorporate groundwater processes into the modelling scheme.

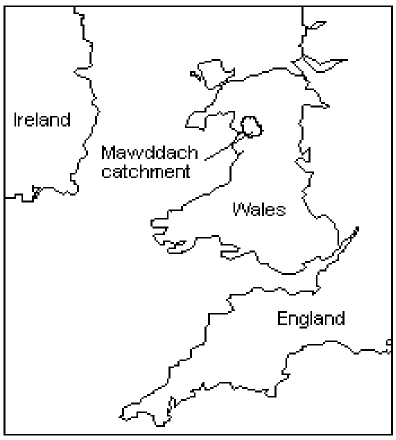
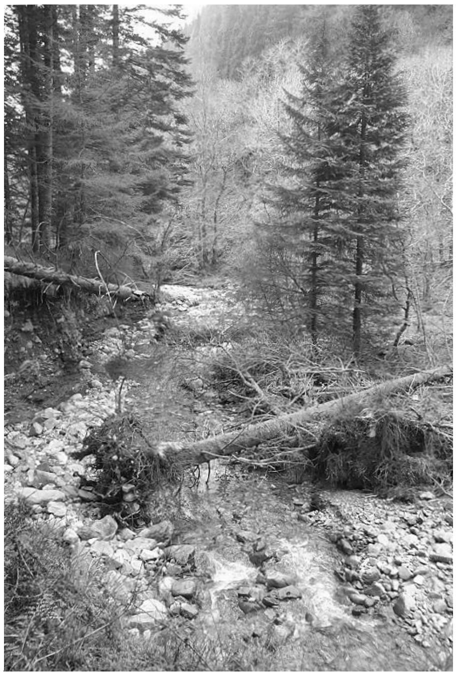


Figure 1. Location of the Mawddach catchment.

Continuous data from 30 raingauges across the area indicate wide variations in rainfall on a microclimate scale between adjacent valleys during the passage of frontal systems or the development of convective storms. High resolution rainfall forecasting therefore forms an essential element of the model.



The combined meteorological and hydrological model developed for the catchment is outlined in figure 3. The MM5 mesoscale meteorological forecasting system, (Grell et al., 1995) provides rainfall input on a 1km grid, and represents a considerable improvement in accuracy compared to interpolation from a regional synoptic scale.

It has been necessary to create a hillslope runoff module as a central interface between meteorological, groundwater and river routing components. The hillslope model is based on a 50m DEM grid SAGA-GIS plays a crucial role in data preparation for this module.

Figure 2. Valley of the Afon Wen, a tributary of the Mawddach, showing thick glacial till forming a river cliff.

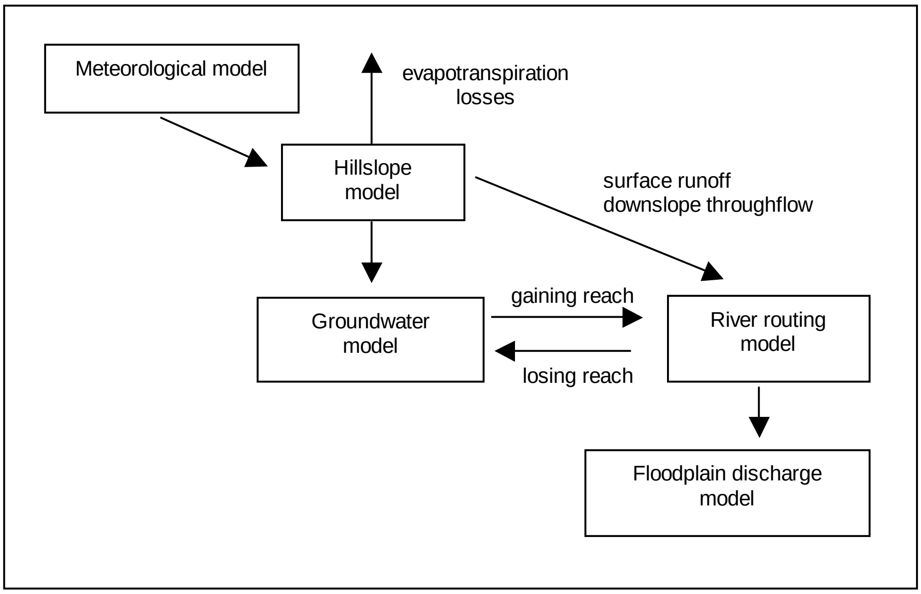


Figure 3. Integrated meteorological / hydrological model for the Mawddach catchment.

FACTORS AFFECTING SOIL HYDROLOGICAL RESPONSE

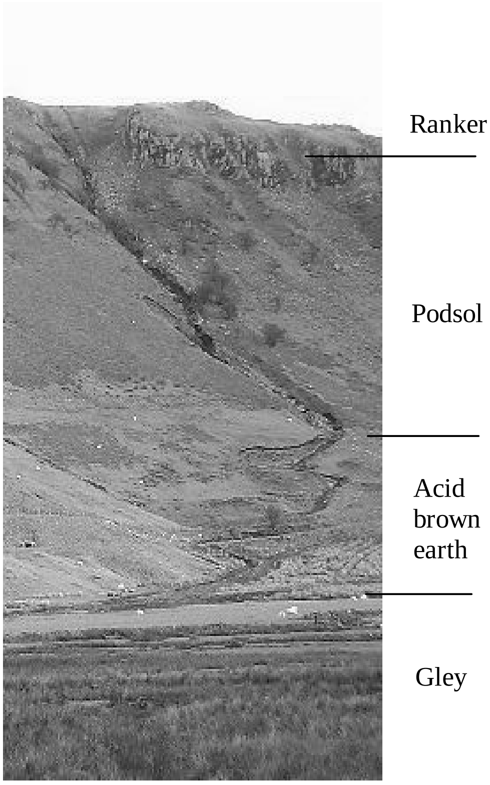


Figure 4. Soil catena at Cwm yr Allt Lwyd

A difficulty in representing the catchment has been the complexity of hydrological response between areas of widely varying topography, land use and geology. Work in formulating the model has concentrated on developing an automated hydrological analysis algorithm based on readily accessible data sets.

Hillslopes within the Mawddach catchment typically exhibit soil catenas, extending from dry ranker soils at steep valley heads, through downslope soils of intermediate moisture content, to saturated gley soils on valley floors. This sequence may be strongly modified locally by geological conditions. Parent materials range from hard igneous and Palaeozoic sedimentary strata to poorly consolidated glacial and periglacial deposits, along with thick peat accumulations.

A significant proportion of the catchment is forested with a mixture of conifer plantations and native oak woods, in addition to wet willow-birch associations on flood plains. Much of the forest has been allowed to reach an age in excess of 50 years. The presence of mature open forest on hillslopes leads to considerably increased soil depth. This effect is observed for both broadleaf woodland and conifer plantations. A proposed mechanism is the increase in humidity within the woodland canopy, leading to profuse growth of mosses which trap downslope sediment movement and provide organic soil input (Hall and Cratchley, 2005). Soil profiles are rapidly depleted within a year of clear felling (figure 6).

A useful approach to delimiting hydrological response units is the HOST (Hydrology of Soil Types) classification of the UK Centre for Ecology and Hydrology. This recognises 29 classes of soil which have characteristic properties of infiltration and runoff. The system is based on a grid with axes representing scales of wetness and permeability variation with depth (figure 5). It is found that particular combinations of parent material, position within the soil catena and vegetation cover can be linked to HOST soil classes. Examples are given in table 1.

		drier types			**intermediate**			**wetter types**	
	SUBSTRATE HYDROGEOLOGY	MINERAL SOILS						PEAT SOILS	
		Groundwater or aquifer	No impermeable or gleyed layer within 100cm	Impermeable layer within 100cm or gleyed layer at 40-100cm		Gleyed layer within 40cm			
				IAC > 7.5	IAC <= 7.5	IAC < 12.5	IAC >= 12.5	Drained	Undrained
permeability increases downwards	Chalk	Normally present and at >2m	1	13		14		15	
	Limestone		2						
	Weakly consolidated, macroporous, by-pass flow uncommon		3						
uniform permeability	Strongly consolidated, non- or slightly porous, by-pass flow common		4						
	Unconsolidated macroporous, by-pass flow very uncommon		5						
	Unconsolidated microporous, by-pass flow common		6						
	Unconsolidated macroporous, by-pass flow very uncommon	Normally present and at <= 2m	7						
	Unconsolidated microporous, by-pass flow common		8			9	10	11	12
permeability decreases downwards	Slowly permeable	No significant groundwater or aquifer	16	18	21	24		26	
	Impermeable (hard)		17	19	22			27	
	Impermeable (soft)			20	23	25			
	Eroded peat							28	
	Raw peat							29	

Figure 5. The HOST classification, after Boorman et al., 1995. IAC represents integrated air capacity of the soil

Figure 6a. Thick soil profile (1.5m) beneath forestry at Hermon

Figure 6b. Reduced soil profile (0.5m) beneath a clear felled hillslope, Hermon

	Dry		Intermediate		Wet	
Material	Grass/moor	Forest	Grass/moor	Forest	Grass/moor	Forest
peat	13	13	14	14	12	11
boulder clay	16	18	24	21	26	26
dolerite	19	17	22	22	27	26
Maentwrog shale	23	22	25	25	29	27

Table 1. Examples of HOST classes linked to soil site

HOST classes are found to have characteristic values for soil depth and texture, which in turn can be used to model infiltration, hydraulic conductivity and runoff during storm events.

HILLSLOPE HYDROLOGICAL MODEL

SAGA-GIS has been used effectively to generate 50m gridded data for Kirkby wetness index (Bevan, 1997), as shown in the example of figure 7. Data is output in Arc Info grid format for transfer to the hillslope model following procedures outlined by Olaya (2004).

An overall algorithm for hillslope infiltration and runoff calculation is shown in figure 8.

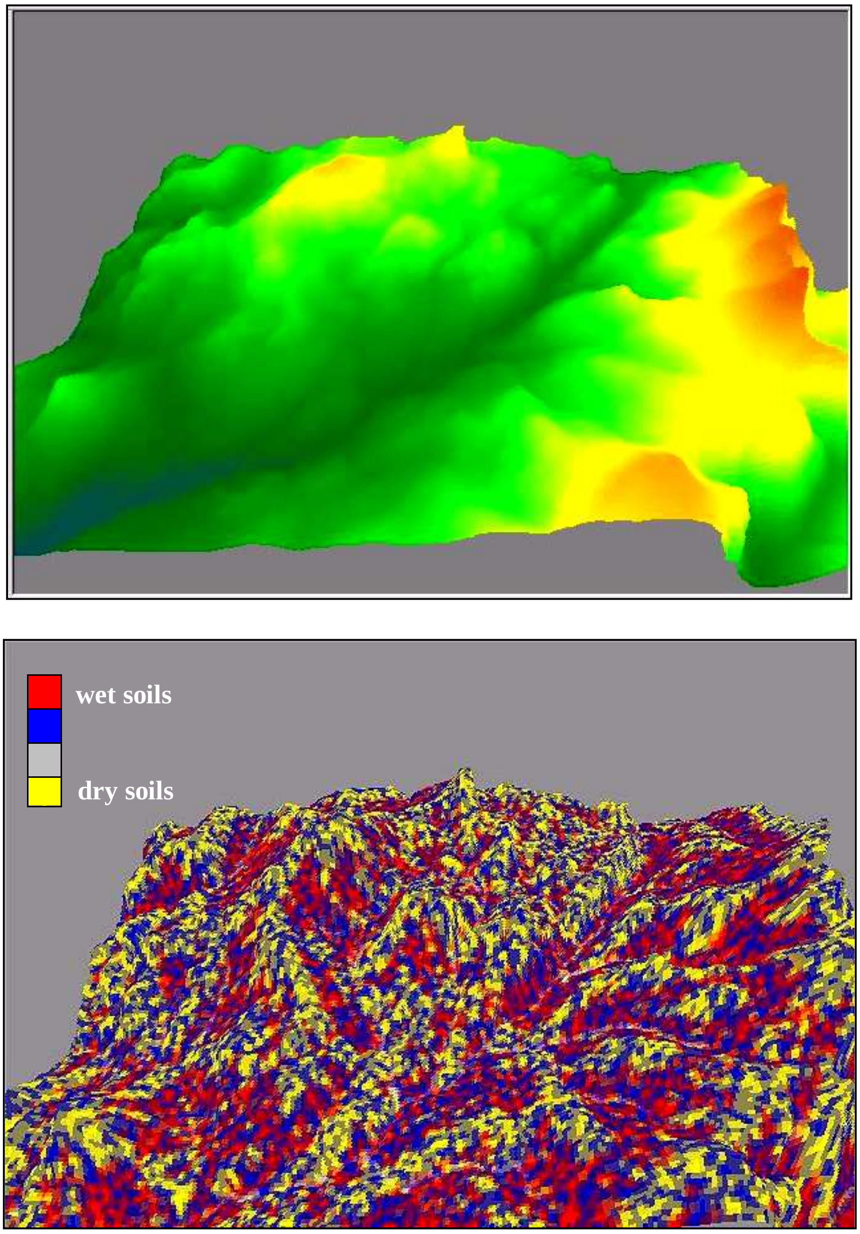


Figure 7. SAGA-GIS three dimensional views of the fault-guided Wnion valley within the Mawddach catchment. The glaciated Aran mountain range is seen to the right. Areas of high predicted soil moisture occur correctly within the concave cirque basins and along the lower slopes of the fault trough.

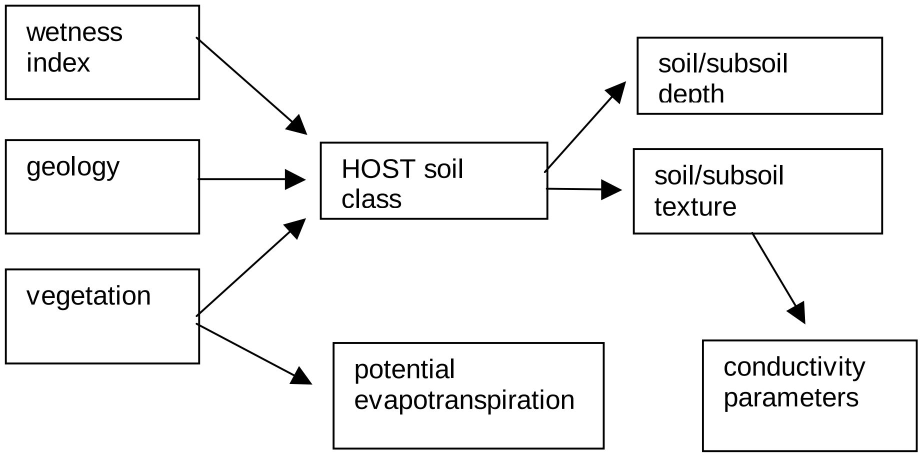


Figure 8. Schematic diagram for hillslope infiltration and runoff calculation.

Geology and vegetation data sets are prepared using Mapmaker vector graphics software (Mapmaker, 2003). This package allows the easy input of shapes as an overlay to a bitmap image, the allocation of *styles* to polygons, and output of the resultant map in Arc View shape file format. (figure 9). Geology is traced from scans of British Geological Survey 1:50 000 drift edition maps. Land use is traced from 1:25 000 colour air photographs. SAGA-GIS allows the conversion of the Arc View shape files to 50m Arc Info grid format for input to the hillslope model.

Automatic allocation of HOST soil classes is carried out by the program, and soil depth and texture values are allocated according to the observed field characteristics of each soil class. Hydraulic conductivity parameters can then be specified from the soil texture (table 2).

		M	K_s	porosity	residual
Topsoils	Coarse	0.2740	60.000	0.35	0.05
	Medium	0.1528	12.061	0.40	0.10
	Medium fine	0.2025	2.272	0.45	0.20
	Fine	0.0919	24.800	0.50	0.35
	Very fine	0.0936	15.000	0.55	0.50
Subsoils	Coarse	0.3424	70.000	0.35	0.05
	Medium	0.1445	10.755	0.40	0.10
	Medium fine	0.1789	4.000	0.45	0.20
	Fine	0.0793	8.500	0.50	0.35
	Very fine	0.0680	8.235	0.55	0.50
Organic		0.1694	8.000	0.50	0.35

Table 2. Soil hydraulic conductivity parameters. M: van Genuchten m parameter, K_s : saturated conductivity (cm/day). Data sources: Nemes at al. (2001), Open University (1995).

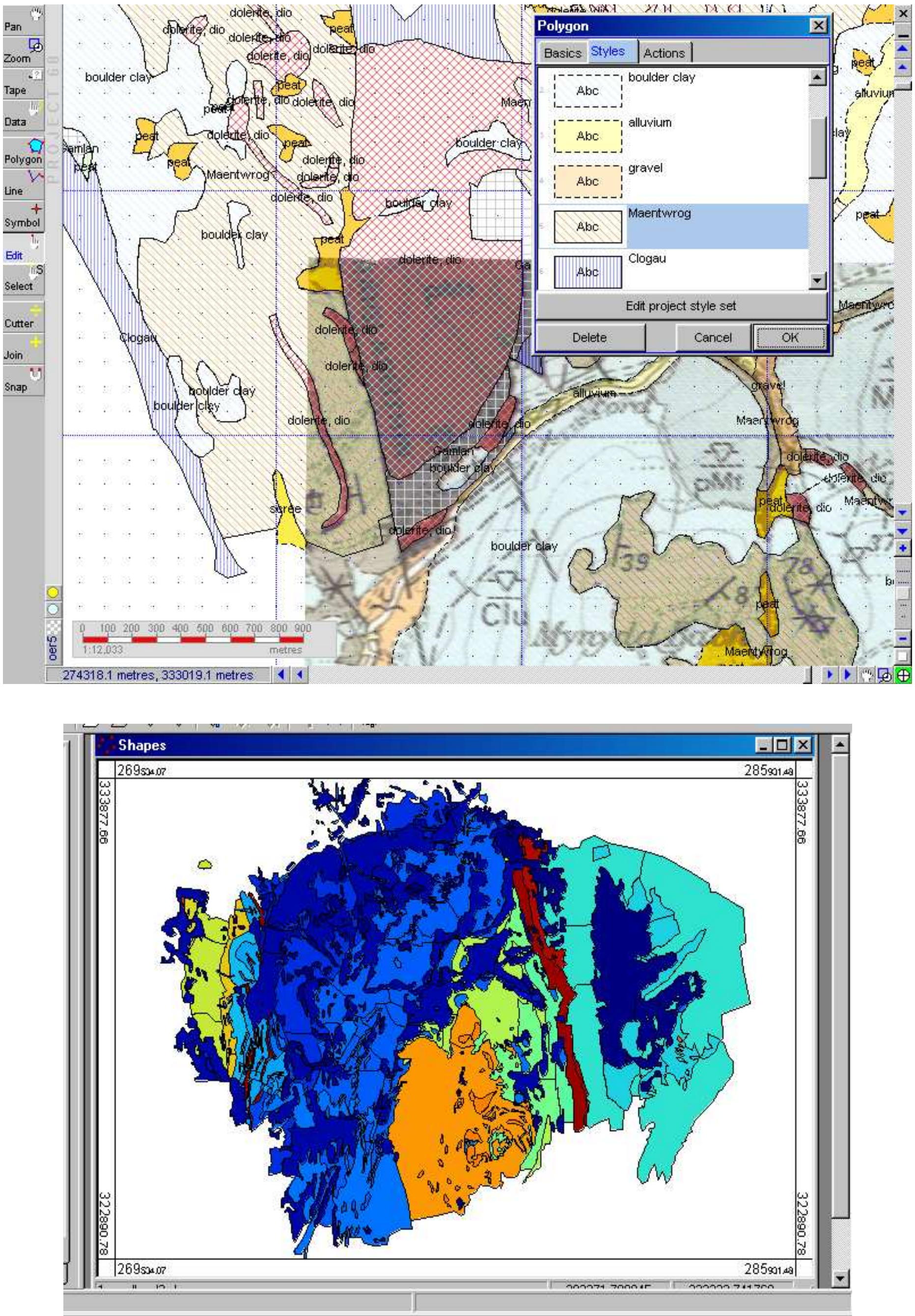


Figure 9. (above) Use of Mapmaker software to prepare a geological map of an area of the Mawddach catchment. (below) Arc View geology shape file imported into SAGA-GIS. The map is subsequently converted to 50m Arc Info grid format for transfer to the hillslope model.

Hydraulic conductivity of the soil is not constant, but varies greatly with effective saturation. Conductivity values fall rapidly to low levels as soils dry, and pore water is retained increasing strongly by capillary forces. An equation has been proposed by van Genuchten (1980) for the calculation of soil conductivity as a function of effective saturation, depending on a parameter m related to soil texture. Typical values of m are 0.274 for coarse sandy soil, down to 0.094 for fine silty soil. The van Genuchten equation is:

$$\frac{K(\theta)}{K_s} = \left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^{1/2} \left[1 - \left(1 - \left\{\frac{\theta - \theta_r}{\theta_s - \theta_r}\right\}^{1/m}\right)^m\right]^2$$

where θ is soil moisture content, subscript s refers to moisture content at saturation, and r refers to soil water retained when the soil is dry.

Figure 10. Runoff and soil throughflow monitoring site, Pared yr Ychain

Each HOST soil class is found to have a characteristic van Genuchten m parameter, allowing the calculation of varying hydraulic conductivity during the simulation of a storm event.

Eight experimental sites have been established in the Mawddach catchment to monitor surface runoff and throughflow in the upper 1.5m of soil, as a means of validating the model output (figure 10).

The volume of rainfall over areas of vegetation can be reduced by processes of evapotranspiration, which include the release of water vapour from leaf pores and direct evaporation from leaf surfaces. Work is currently underway to incorporate evapotranspiration into the hillslope model using meteorological data from the MM5 mesoscale model, and to carry out a sensitivity analysis to determine the extent to which effective rainfall is reduced by evapotranspiration losses during storm events. This may be significant where wind speeds are high.

DISCUSSION

The combined hydrological/meteorological model for the Mawddach catchment is currently being tested by simulating historical flood events of known magnitude. SAGA-GIS has been central to the automated analysis of soil hydrological characteristics across the catchment. Soil parameters determined through use of GIS data allow the estimation of runoff, shallow throughflow and infiltration during storm events.

Output from the hillslope model is fed to a regional MODFLOW groundwater model, and to the River2D program for river routing and the simulation of flood plain inundation during storm events.

REFERENCES

Beven K.J., 1997. Distributed hydrological modelling. Wiley.

Boorman D.B., Hollis J.M. and Lilly A., 1995. Report No.126. Hydrology of soil types: a hydrologically-based classification of the soils of the United Kingdom. Institute of Hydrology.

Grell G.A., Dudhia J. and Stauffer D.R., 1995. A description of the Fifth-generation Penn State/NCAR Mesoscale Model (MM5). NCAR Technical Note TN-398 + STR. National Center for Atmospheric Research, Boulder, Colorado.

Hall G. and Cratchley R., 2005. The role of forestry in flood management in a Welsh upland catchment. Proceedings of the 45th Congress of the European Regional Science Association, Amsterdam.

Mapmaker, 2003. Map Maker – the Manual. Mapmaker Ltd, Carradale, Scotland.

Nemes A., Wösten, J.H.M. and Lilly A., 2001. Development of soil hydraulic pedotransfer functions on a European scale: their usefulness in the assessment of soil quality. Proc. 10th International Soil Conservation Organisation meeting, Purdue University.

Olaya V., 2004. A gentle introduction to SAGA GIS. Göettingen University.

Open University, 1995. S268 Physical Resources and Environment, Block 3: Water Resources. Open University Press.

van Genuchten, M.T., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Science Soc. America Journal, 44.