4. Integrated catchment modelling

4.1 Integrated meteorological-hydrological models

The approach required for hydrological modelling depends largely on the size of the drainage basin being modelled. Uhlenbrook, Roser and Tilch (2003) identify three size categories:

- Micro-scale basins of up to1km^2. At this scale, the patterns of soil types and land use play a major role within the model. Rainfall may be considered constant across the basin at any particular time, so input from a single raingauge will be sufficient.
- Mesoscale basins, between 1km^2 and 1000km^2. Patterns of soil types and land use are again important, but rainfall may now show considerable variation across the basin at any particular time. Steps must be taken to represent rainfall sequences with sufficient spatial accuracy.
- Macroscale basins over 1000km^2. At this scale, the pattern of rainfall becomes the major factor controlling river flows. Soil and landuse characteristics can be represented by averaged parameters over large regions of the model.

The Mawddach catchment above the tidal limits of the Mawddach and Wnion has an area of approximately 280km^2. This clearly falls into the category of a mesoscale basin, where the spatial patterns of both rainfall and land surface characteristics across the basin will be important factors.

Within a mesoscale basin, a number of hydrological processes will be operating, including: hillslope surface runoff, shallow throughflow, infiltration to groundwater and resurgence from groundwater, river routing, and overbank flooding. To these may be added river-tidal interactions for a river system reaching the coast. Attempts have been made by various hydrologists to combine the different processes into single integrated models.

The first step towards a fully integrated catchment model is often the linking of hillslope, river routing and groundwater processes. A successful example is the System Hydrologique European (SHE) model. This uses a surface grid, groundwater grid, and river channel model aligned along the grid (fig.4.1).

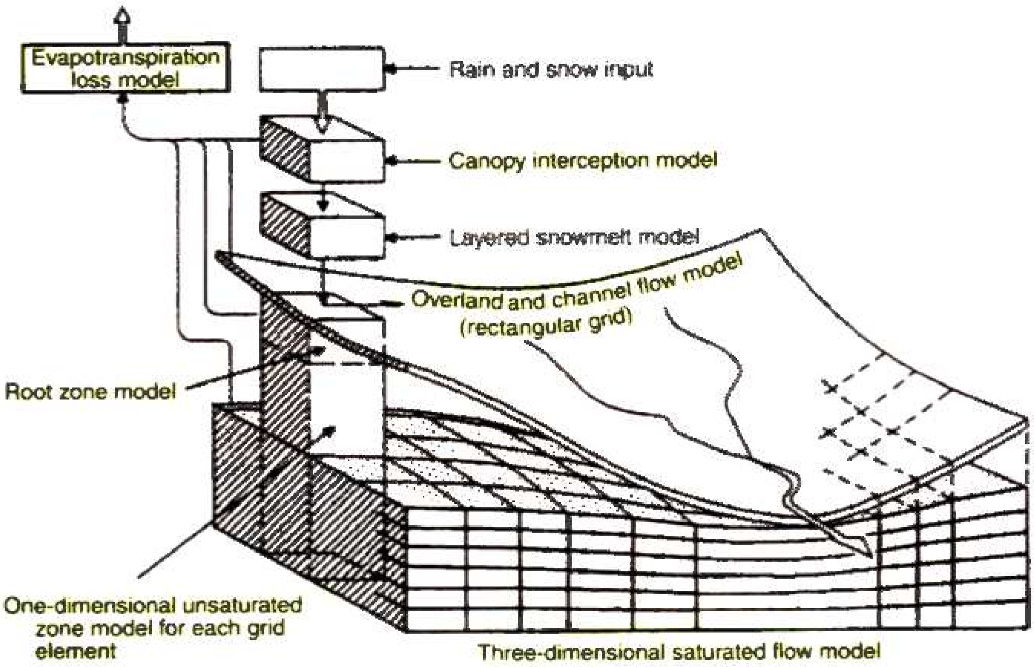
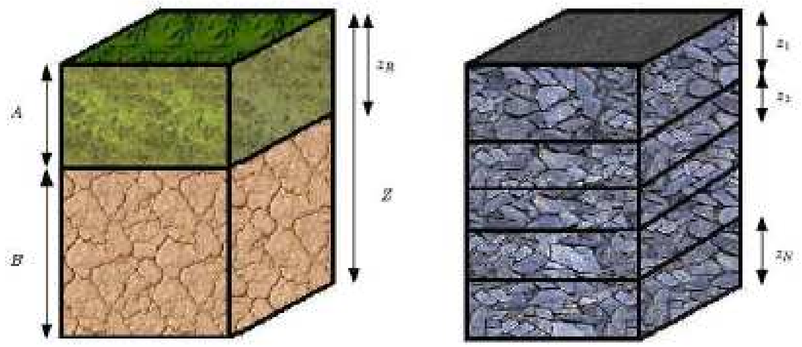


Figure 4.1: Schematic diagram of the grid-based catchment discretisation in the SHE model. From: Refsgaard J.-C. and Storm B., 1995.

An evaluation of the SHE model by Heathcote, Lewis and Soley (2004) concludes that the large number of parameters which need to be defined can make the model costly in time to collect field data. Some parameters cannot be measured directly, so calibration against recorded hydrographs is required. The model then starts to loose its independence as a process-based system. A further limitation is that localised variations in rainfall in a complex terrain may not be represented when rainfall input is averaged from a limited field distribution of raingauges.

Another approach to integrated modelling is the Soil Moisture Distribution and Routing (SMDR) model developed by Cornell University (2003). Central to this program is the representation of the hillslope soil zone as superimposed systems (fig.4.2):

- Functional layers, giving an upper zone of active evapotranspiration and a lower zone of water transmission.
- Structural layers, with properties of hydraulic conductivity, residual and saturated water capacity dependant on soil parent material and morphology.



(a) 2 *Functional* layers (b) *N Structural* layers

Figure 4.2: Soil zone representations in the SMDR model

A downward linkage is maintained with a groundwater model. Soil water may infiltrate to groundwater storage, and groundwater may re-enter the base of the soil zone when the water table rises sufficiently.

Surface water moves downslope by kinematic wave. Shallow throughflow within the soil zone moves downslope in accordance with Darcy's equation for flow through porous material. River routing then completes the model.

An alternative approach to integrated modelling is to incorporate industry-standard models for different stages of the hydrological cycle as modules of a larger system:

Heathcote, Lewis and Soley (2004) present a combined runoff and recharge model which links the MODFLOW groundwater model to their 4R code for handling hillslope runoff and river routing. The purpose of this system is primarily for evaluating fluctuations in water resources within aquifers over a timescale of months.

The 4R model separately models the fast surface runoff and slower downslope throughflow within the soil zone, in addition to infiltration to groundwater storage (fig.4.3). Evapotranspiration is calculated using the Penman-Monteith equation. River routing is carried out within the 4R package by applying appropriate flow delay times between river cells. River bed water loss or resurgence from groundwater is handled by the STREAM module of the MODFLOW package (McDonald and Harbaugh, 1988).

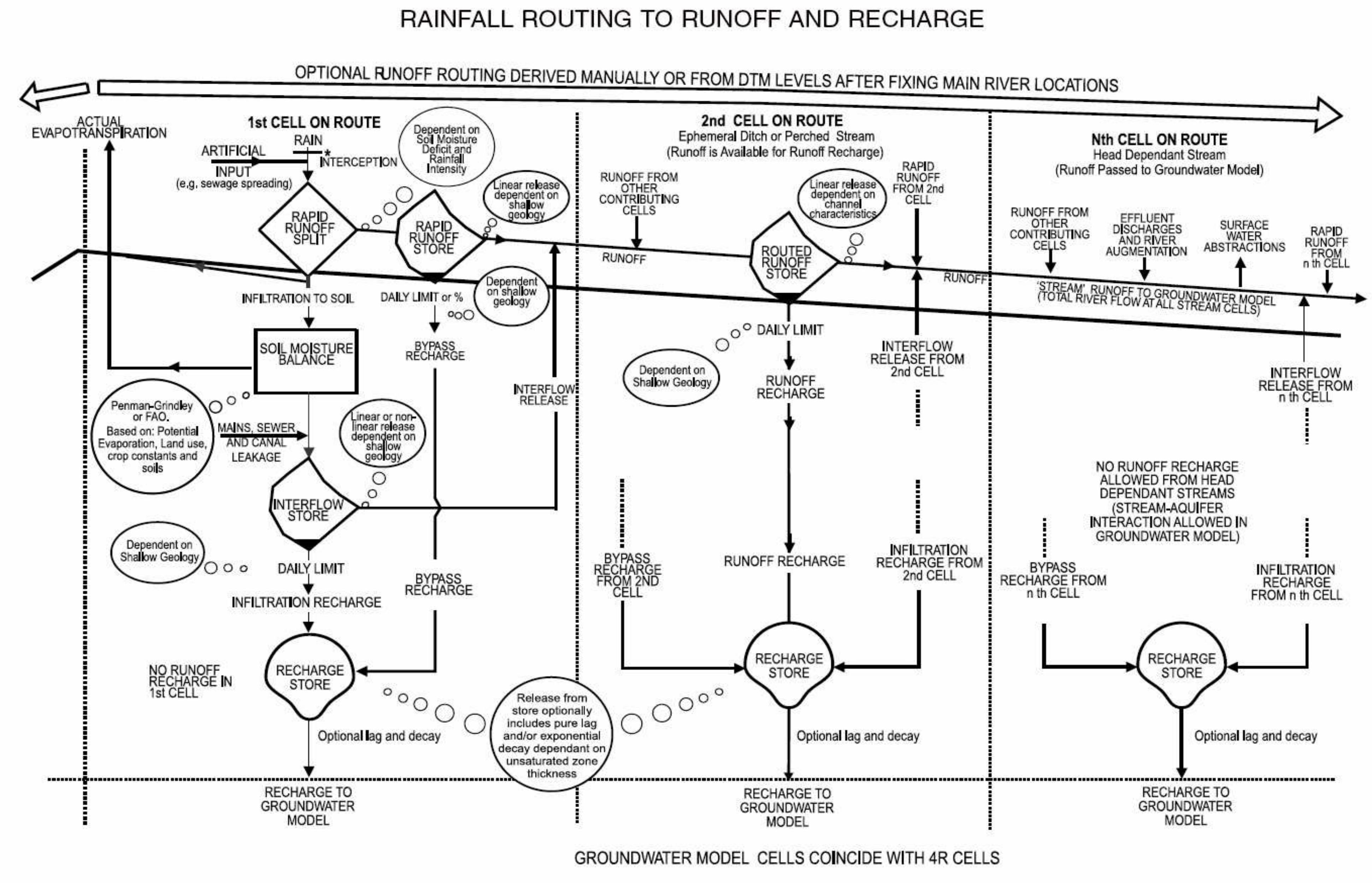


Figure 4.3: Schematic diagram for the 4R hydrological model, from Heathcote, Lewis and Soley, 2004.

Different approaches may be used to link rainfall patterns to hydrological models:

- An assumption of uniform rainfall distribution over the catchment area. This is generally valid only for micro-scale basins.
- Determining rainfall distribution as an average of rain gauge readings in and around the catchment. This is the method used by the HEC-1 model (see section 3.2) in which rainfall is averaged using the Thiessen polygon technique.
- Calculating rainfall distribution as a base value plus an altitude correction, on the assumption that rainfall increases predictably with height. This approach has been investigated by Lloyd (2005) to improve estimation of monthly precipitation in Britain.

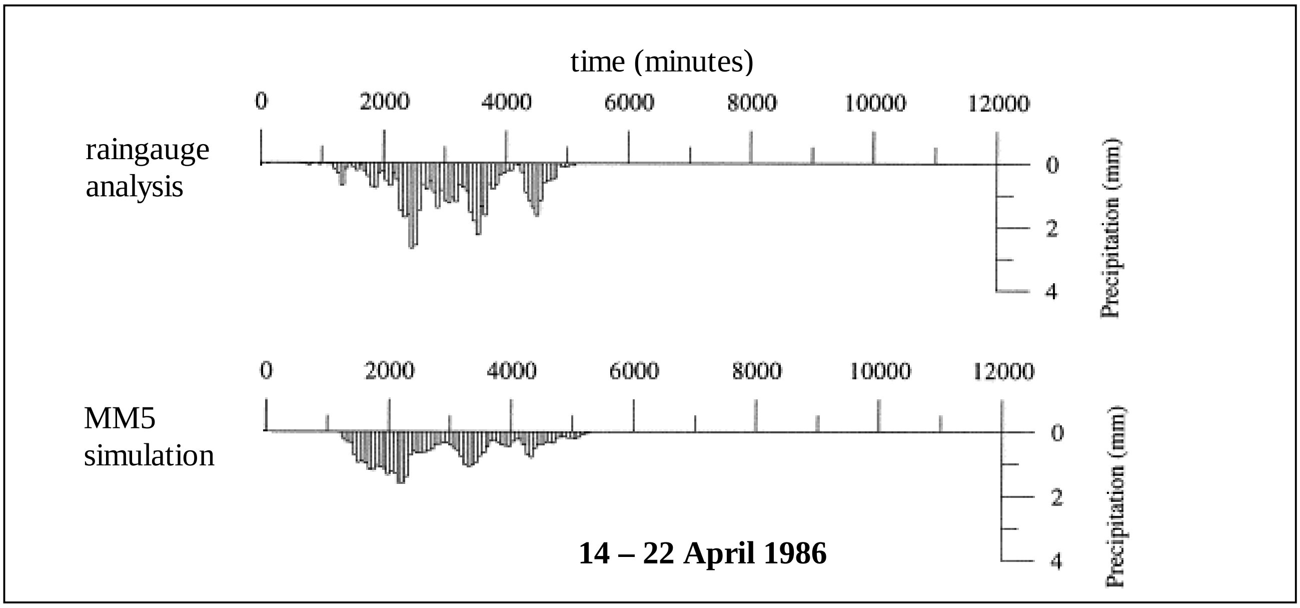
Field studies of rainfall distribution in the Mawddach catchment suggest that none of these methods can provide an adequate solution. Localised variations in rainfall pattern occur between storm events, which can be only poorly correlated with altitude. Meteorological modelling appears to provide a better method of generating reliable rainfall input values for hydrological models. In chapter 2, the MM5 model was used to generate rainfall distributions for the Mawddach catchment.

Incorporation of rainfall models

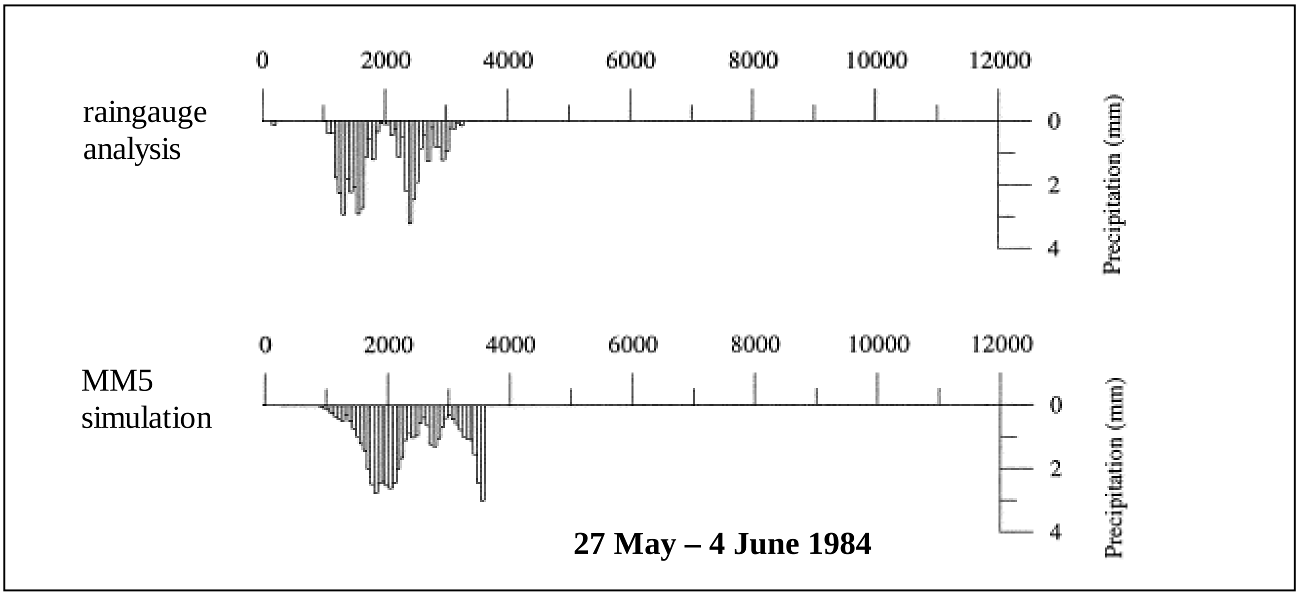
Integrated systems have been developed by several authors which incorporate meteorological models for rainfall input during individual storm events:

Yu et al. (1999) used the MM5 mesoscale model in a flood prediction system for the Susquehanna River, Pennsylvania. Rainfall distribution patterns provide input to the authors' Hydrologic Model System. Three example MM5 simulations for storms have been provided (fig.4.4). In each case the MM5 rainfall patterns are compared with a rainfall distribution inferred from a limited array of raingauges across the catchment.

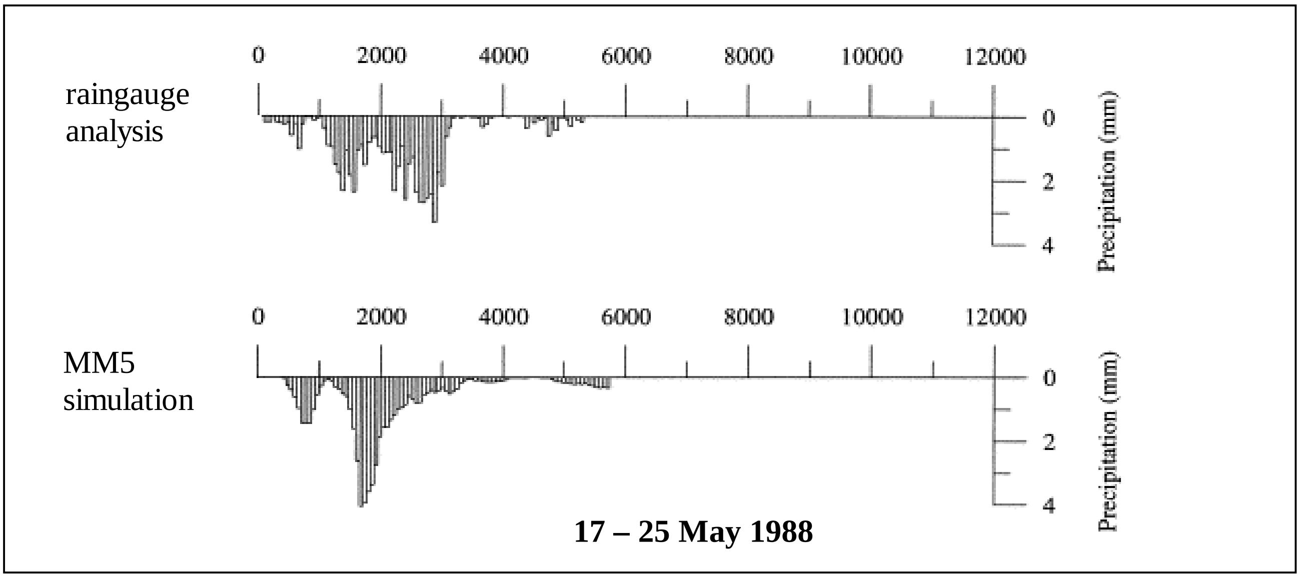
- The April 1986 MM5 result gives similar hourly precipitation totals. The onset of heavy rainfall occurs slightly too early in the model.



14 – 22 April 1986



27 May – 4 June 1984



17 – 25 May 1988

Figure 4.4: MM5 rainfall simulations for storms in the Susquehanna catchment. From: Yu et al. (1999)

- The May-June 1984 MM5 result again gives similar precipitation totals. However, the second heavy rainfall period during the storm is substantially underestimated and a third heavy rainfall event is predicted but not observed.
- The May 1988 MM5 result overestimates rainfall intensity but underestimates rainfall duration for the second heavy rainfall period during the storm.

If the distributions inferred from gauge readings are taken as accurate, then the MM5 simulations capture the essential patterns of rainfall but show significant variations in detail. The authors do not provide rainfall maps to show where errors may be concentrated in relation to catchment topography.

The Hydrologic Model System of Yu et al.(1999) allows for rainfall runoff/infiltration partitioning to be carried out using either the SCS curve numbers method or the Green-Ampt method. It was found the curve numbers method generated results which were more consistent with recorded hydrographs over a range of storms.

Benoit et al. (2000) used the Canadian MC2 meteorological model for flood prediction around the Great Lakes area of North America. Operating in a similar way to MM5, this mesoscale model was able to provide high resolution rainfall input to a hillslope and river routing model. The authors carried out evaluations of the meteorological model in comparison to rainfall plots generated by rainfall radar. It was found that the meteorological model provided more accurate rainfall intensities and distribution patterns than the radar. However, rainfall radar patterns were not affected by errors in the timing of rainfall events as sometimes occurred in rainfall modelling. It was suggested that a combination of the two techniques, with radar used to adjust the timing of rainfall events in the model, could lead to an overall improvement in input quality for the hydrological model.

Requirements for a Mawddach integrated model

On the basis of work carried out in previous sections, a conceptual model has been constructed for hydrological processes within the Mawddach catchment, and forms the basis for an integrated meteorological/hydrological model. The components of the model are shown in fig.4.6:

- Rainfall patterns are sufficiently complex to require a meteorological model. The MM5 mesoscale model has proved suitable, as shown in section 2.4.
- Hillslope runoff and shallow stormflow are central to the model, and are dependant on topography, soil type and vegetation.
- River routing within the upland catchment may involve both sub-critical and super-critical flows.
- Groundwater interactions with surface water were shown to take place, particularly in the deeply incised valleys of Coed y Brenin. However, the rate of groundwater resurgence appears to be too slow to affect the extent of flooding during storm events.
- Modelling of overbank discharge onto floodplains is the primary purpose of the flood prediction system, and is an essential component of the integrated model.
- Tidal interaction with river flow appears to be of negligible importance in influencing flooding above the tidal limits of the estuary, as determined by modelling in section 3.6.
- Sediment movement causes periodic revisions to channel profiles. Modelling of long term sediment transport can be important from a research perspective, but within a single storm event the channel profiles may be considered constant.

The core model for use in operational flood forecasting is therefore considered to consist of: rainfall input, hillslope runoff and storm flow, river routing and overbank discharge onto floodplains.

The software packages MM5 (meteorology), GSTARS (river routing) and River2D (overbank flooding) have proved successful in modelling particular elements of the hydrological system. A new hillslope hydrology module is required to link the functions of these packages. The hillslope module has been developed as part of this research project, and is described in the following sections.

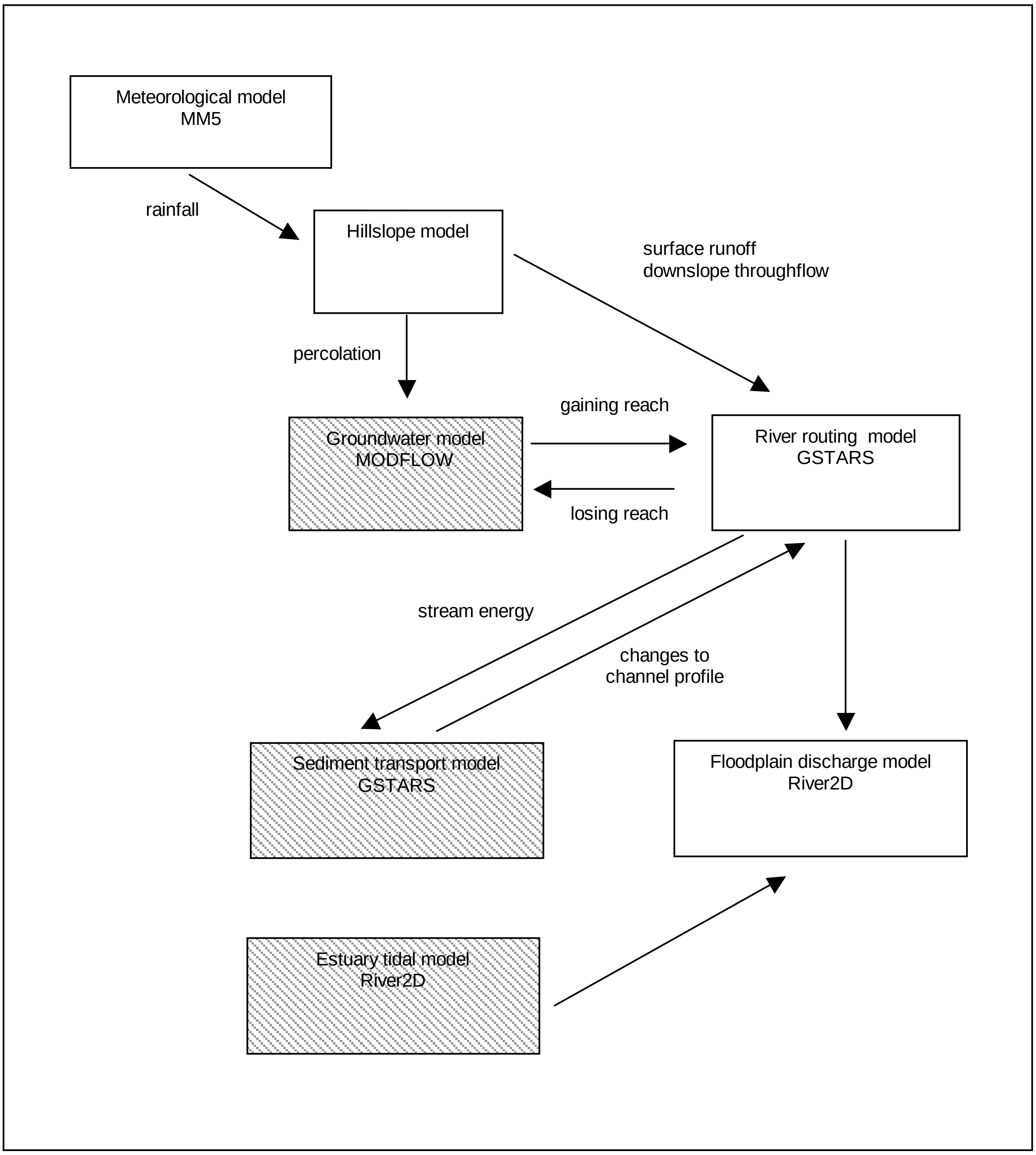


Figure 4.6: Components of the Mawddach integrated model. Operational modules unshaded. Modules not incorporated in the operational model are

Mathematical basis for the hillslope model

Factors important to surface runoff and shallow subsurface flow were found to be: slope angle, upslope contributing area, and soil type - which is in turn dependent on the underlying geology and the vegetation/land use.

Digital elevation data for the Mawddach catchment is available on a 50m grid. The size of the catchment precludes field mapping of soils at a similar grid spacing, so an automated approach to assigning soil characteristics is required.

The problem of efficient soil mapping was addressed by Mew and Ball (1972) in a study in the Rhinog mountains. The authors evaluated a technique of field inspection on a grid with 300m spacing, augmented by analysis of air photographs to identify probable soil boundaries. The map produced was then checked by detailed field mapping. It was found that very few soil boundaries could be inferred accurately from the air photographs, and that some soil types present were missed completely by the sample points. Difficulties arise because soils show a lateral gradation in characteristics, rather than sharp boundaries. Air photographs could, however, identify suitable transect lines along which to examine variations in soil type.

It was shown in section 1.2 that the HOST (Hydrology of Soil Types) system developed by the Institute of Hydrology (Boorman et al., 1995) is suitable for use in hydrological modelling. Each HOST soil class has characteristic properties of texture and depth for topsoil and subsoil layers. This in turn allows the allocation of parameters for use in the calculation of hydraulic conductivity
(van Genuchten, 1980).

An automated mapping algorithm has been developed to allocate HOST soil classes to each 50m grid square of the Mawddach catchment (figure 4.7). Allocations to soil classes can then be checked by field observations, and corrections to the map can be made where necessary.

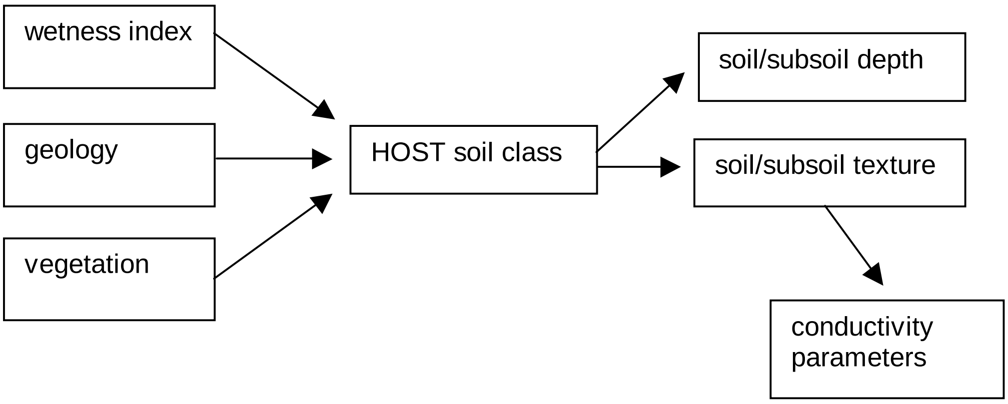


Figure 4.7: Stages in the determination of soil parameters for the hillslope model

Rainwater reaching the ground will infiltrate vertically or run-off laterally at the surface or at shallow depth, depending on soil hydraulic conductivity.

Hydraulic conductivity of the soil is not constant, but varies greatly with effective saturation (fig.4.8). 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 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.

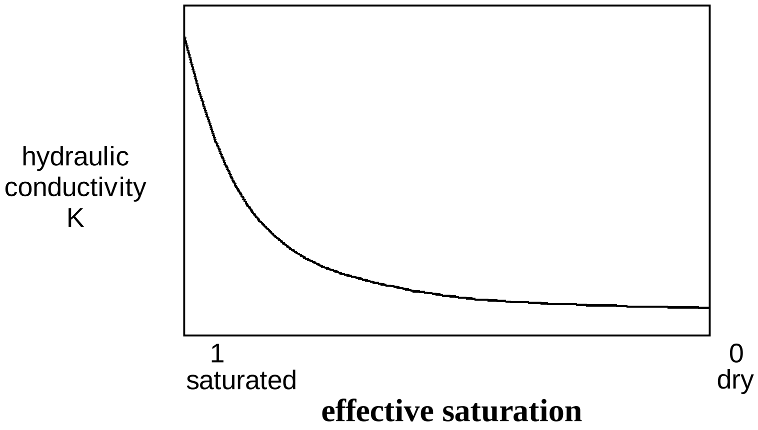


Figure 4.8: Relationship between soil conductivity and effective saturation

A sequence of soil types is typically developed down a hillslope, with drier soils at higher levels where downslope drainage is rapid and upslope contributing area is small (figure 4.9). By contrast, wetter soils develop at the bases of hillslopes where drainage is often slower and the upslope contributing area is large. A quantitative index of wetness at any point is given by the Kirkby index (Bevan, 1997)

$$\ln (a / \tan \beta)$$

where a is upslope contributing area and β is slope angle.

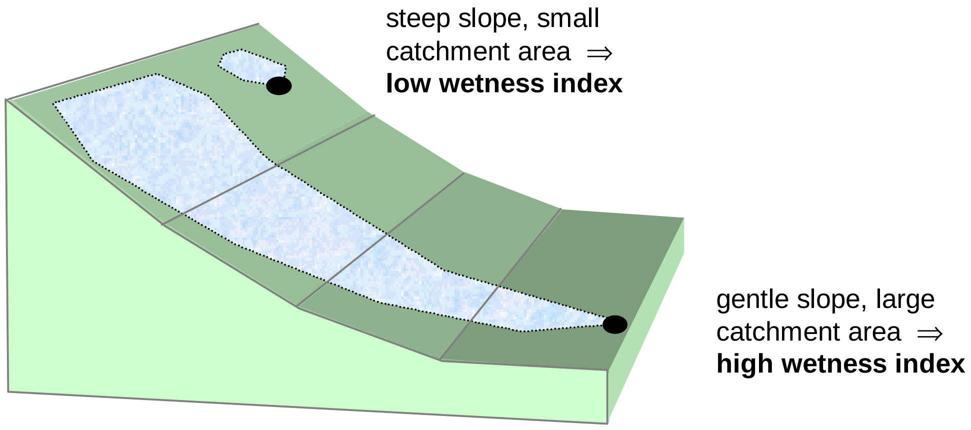
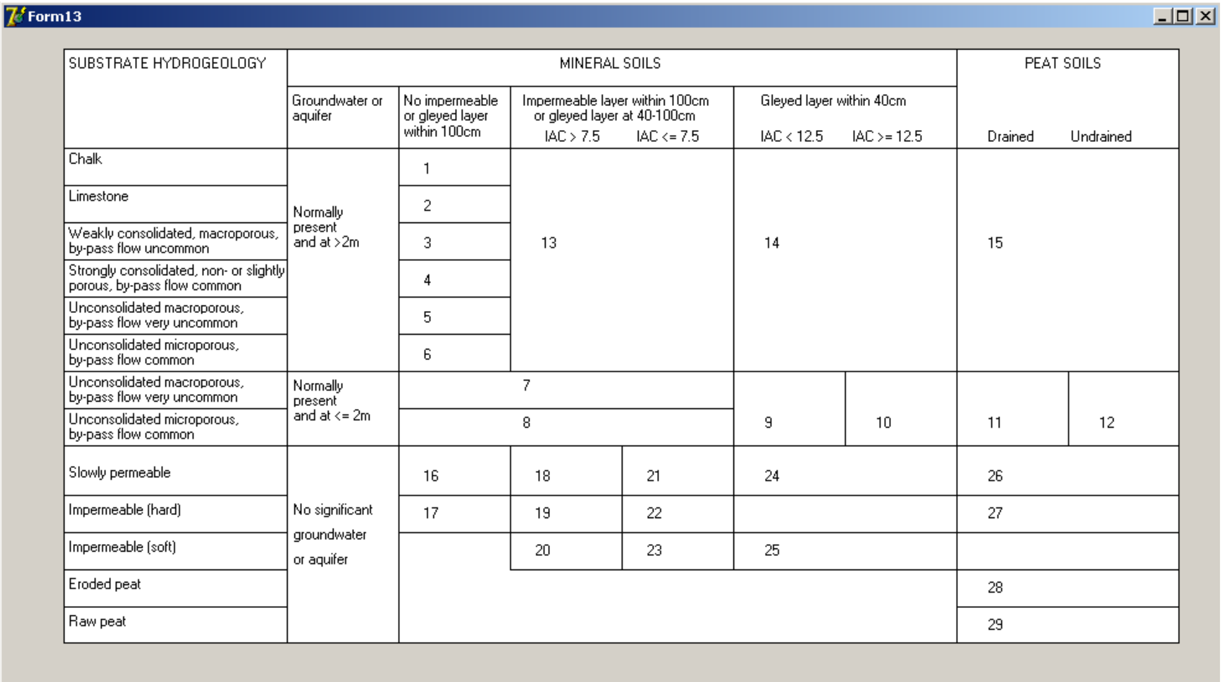
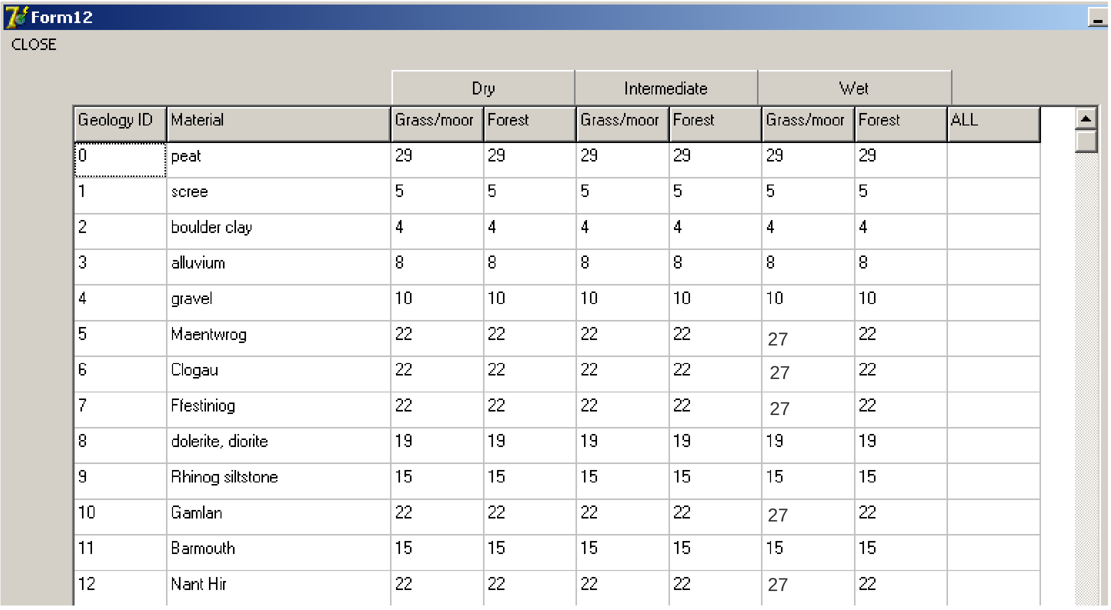


Figure 4.9: Factors determining Kirkby wetness index

The digital elevation model can provide slope angles and upslope catchment areas for each 50m grid square, allowing the Kirkby wetness index values to be calculated. Classification of geological parent material has also been prepared on a 50m grid for the catchment. The Kirkby wetness index, represented on a three-point scale *dry – intermediate -wet* is related to geology through a lookup table (fig.4.10) to generate HOST soil classes.



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 IAC > 7.5	IAC <= 7.5	Gleyed layer within 40cm IAC < 12.5	IAC >= 12.5	Drained	Undrained
Chalk	Normally present and at >2m	1	13		14		15	
Limestone		2						
Weakly consolidated, macroporous, by-pass flow uncommon		3						
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			9	10	11	12
Unconsolidated microporous, by-pass flow common		8						
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	

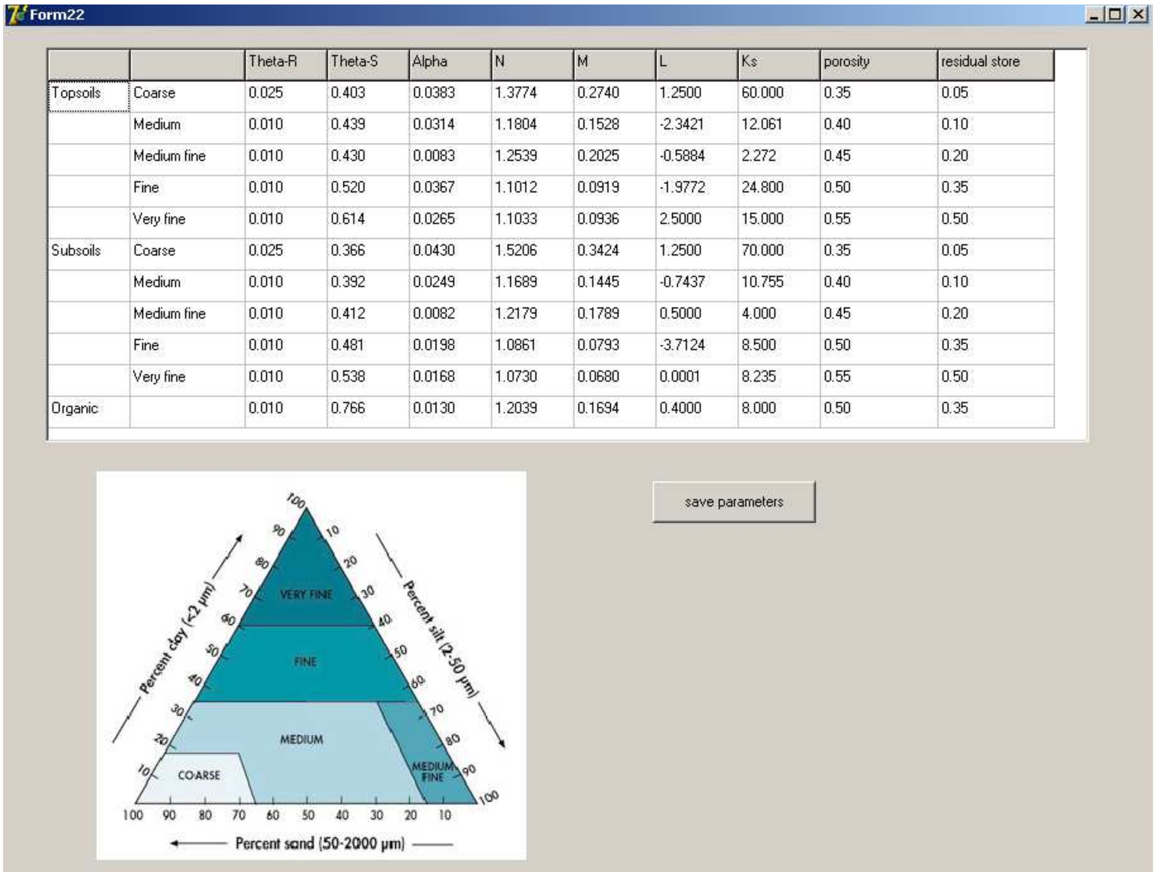


		Dry		Intermediate		Wet		
Geology ID	Material	Grass/moor	Forest	Grass/moor	Forest	Grass/moor	Forest	ALL
0	peat	29	29	29	29	29	29	
1	scree	5	5	5	5	5	5	
2	boulder clay	4	4	4	4	4	4	
3	alluvium	8	8	8	8	8	8	
4	gravel	10	10	10	10	10	10	
5	Maentwrog	22	22	22	22	27	22	
6	Clogau	22	22	22	22	27	22	
7	Ffestiniog	22	22	22	22	27	22	
8	dolerite, diorite	19	19	19	19	19	19	
9	Rhinog siltstone	15	15	15	15	15	15	
10	Gamlan	22	22	22	22	27	22	
11	Barmouth	15	15	15	15	15	15	
12	Nant Hir	22	22	22	22	27	22	

Figure 4.10: Lookup table for allocation of HOST soil classes to hillslope grid squares

Field investigations have shown that thick soils gradually develop on hillslopes beneath both deciduous and coniferous forest, reaching their maximum thickness as the woodland becomes mature after 30 years. Forest soils can be rapidly eroded after clear felling. *Grass/moorland* and *Forest* variants giving different HOST classes are therefore allowed for each soil/wetness grouping.

HOST classes provide a link to the vanGenuchten infiltration equation. Each HOST class is characterised by its typical topsoil and subsoil texture and depth. Data provided by Nemes, Wösten and Lilly(2001), and Kumar and Purandara (2003) is used to allocate vanGenuchten parameters $\theta_{R,}$ $\theta_{S,}$ α, N, M, L and K_S to each HOST class, based on soil texture (fig.4.11).



		Theta-R	Theta-S	Alpha	N	M	L	Ks	porosity	residual store
Topsoils	Coarse	0.025	0.403	0.0383	1.3774	0.2740	1.2500	60.000	0.35	0.05
	Medium	0.010	0.439	0.0314	1.1804	0.1528	-2.3421	12.061	0.40	0.10
	Medium fine	0.010	0.430	0.0083	1.2539	0.2025	-0.5884	2.272	0.45	0.20
	Fine	0.010	0.520	0.0367	1.1012	0.0919	-1.9772	24.800	0.50	0.35
	Very fine	0.010	0.614	0.0265	1.1033	0.0936	2.5000	15.000	0.55	0.50
Subsoils	Coarse	0.025	0.366	0.0430	1.5206	0.3424	1.2500	70.000	0.35	0.05
	Medium	0.010	0.392	0.0249	1.1689	0.1445	-0.7437	10.755	0.40	0.10
	Medium fine	0.010	0.412	0.0082	1.2179	0.1789	0.5000	4.000	0.45	0.20
	Fine	0.010	0.481	0.0198	1.0861	0.0793	-3.7124	8.500	0.50	0.35
	Very fine	0.010	0.538	0.0168	1.0730	0.0680	0.0001	8.235	0.55	0.50
Organic		0.010	0.766	0.0130	1.2039	0.1694	0.4000	8.000	0.50	0.35

Figure 4.11. Soil and subsoil hydrological properties related to texture

Characteristic values for soil and subsoil porosity and residual water capacity are also related to texture, using data provided by the Open University (1995).

Water flow

The hillslope model determines the surface runoff and throughflow which is able to enter the river system. Water released into river cells provides an input to the separate river routing code. Drainage may also occur downwards to groundwater storage.

Uhlenbrook, Roser and Tilch (2003) provide a conceptual model for their study of a mesoscale basin in the Black Forest, Germany, which has strong similarities with the Mawddach catchment in terms of topography, hard rock geology, (peri)glacial deposits and a combination of forest and grass/moorland vegetation. The authors use a grid of 50m cells, with each cell allowing the computation of shallow throughflow and surface runoff as appropriate (fig.4.12).

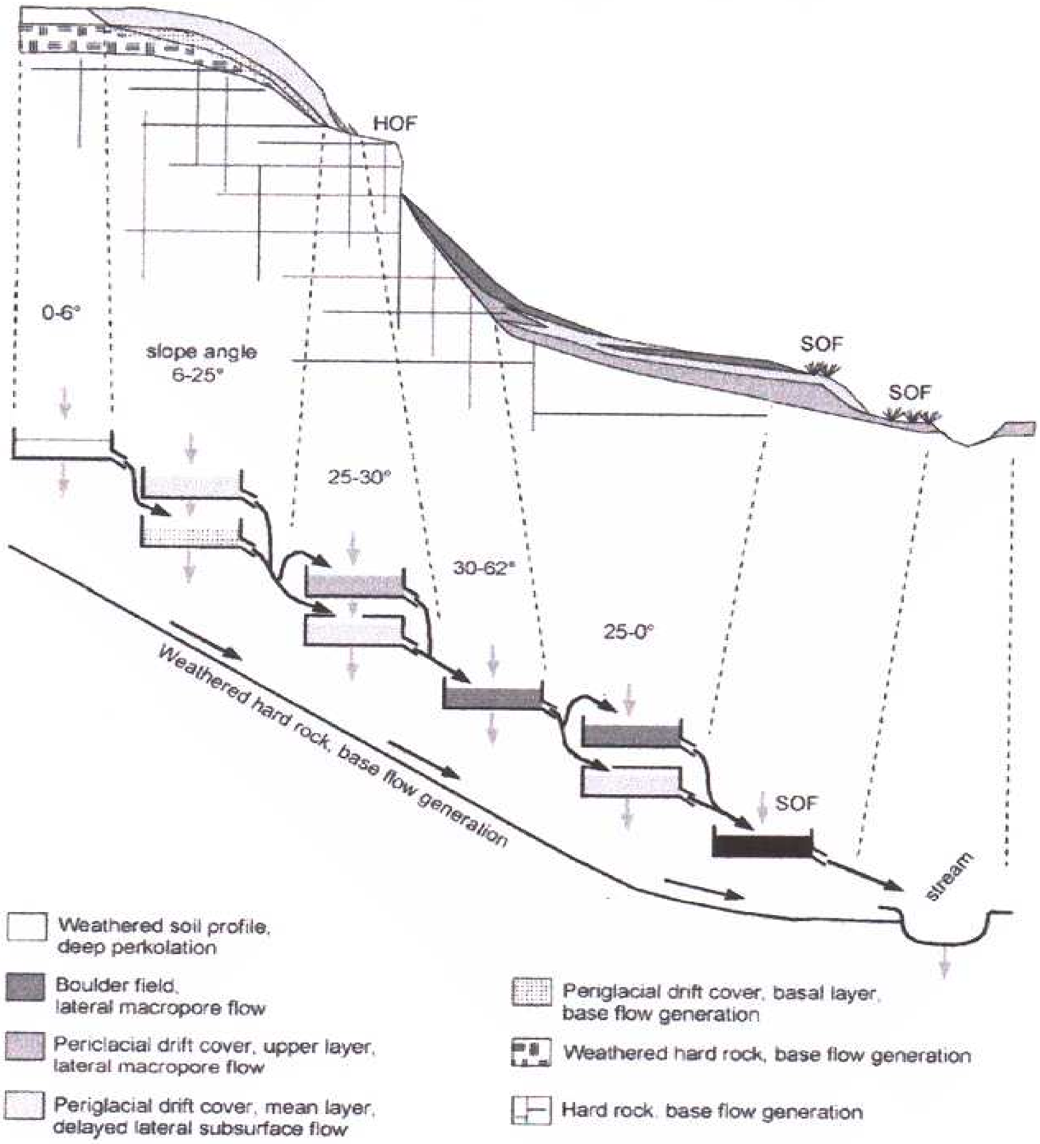


Figure 4.12: Conceptual cascade store model for the Brugga Basin, Black Forest, Germany. From Uhlenbrook, Roser and Tilch (2003)

Following the approach of Uhlenbrook et al., and also the SMDR model of Cornell University (2003), the Mawddach hillslope model uses 50m grid elements. Each is composed of four topsoil layers and four subsoil layers, with actual thicknesses determined by the soil depth (fig.4.13). Inflow consists of rainfall at the grid square, plus downslope flow from adjacent cells.

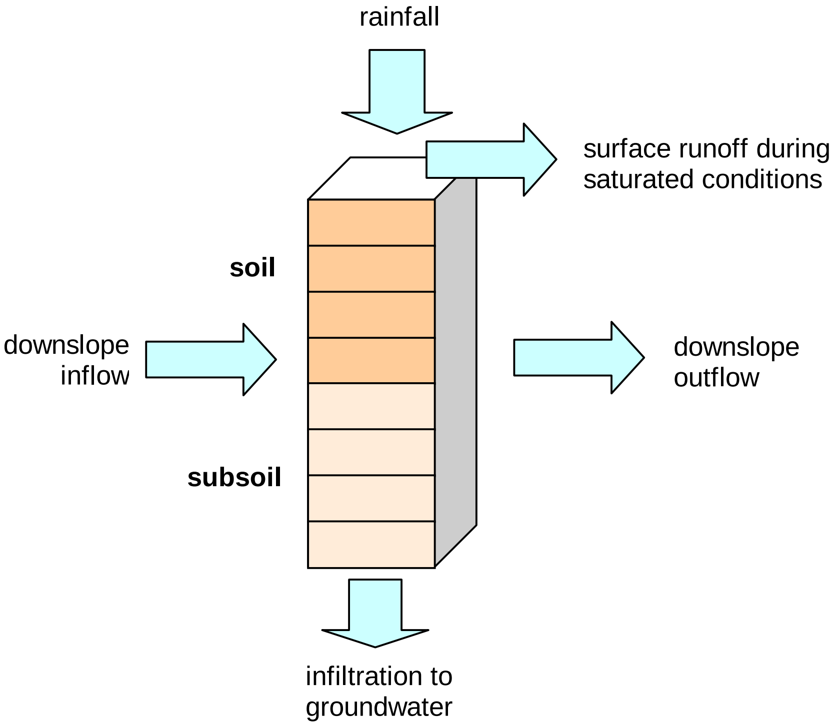


Figure 4.13: Water flows associated with a cell of the Mawddach hillslope model

Computational processes allow the downwards movement of soil water to groundwater storage or lateral downslope outflow according to the Darcy equation for porous media:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right)-W = S\frac{\partial h}{\partial t}$$

where h terms refer to hydraulic head, K parameters are hydraulic conductivities, W is a sink and source term, and S is water storage (see section 3.1).

The direction of maximum slope is determined, and outflow is partitioned to a maximum of two downslope cells (fig.4.14) according to angle.

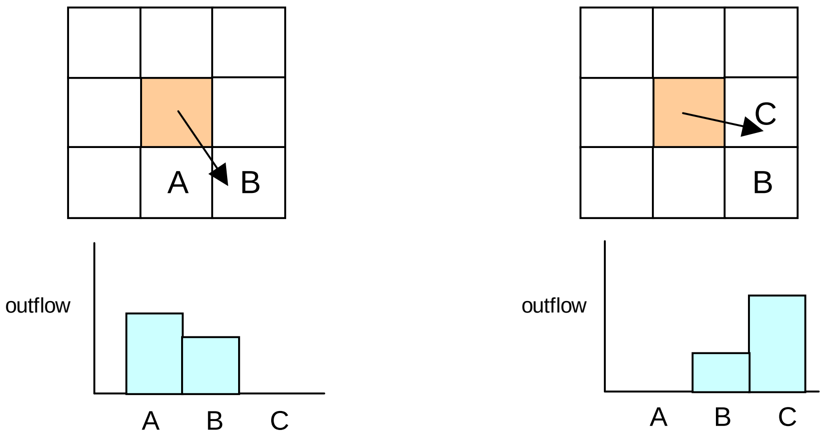


Figure 4.14: Partitioning of downslope flow depending on slope direction

If complete saturation of the topsoil layers occurs during a time interval, the excess water is released to downslope cells as surface runoff. Flow is determined using the Kinematic wave relationship

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = r$$

where:

$\frac{\partial A}{\partial t}$ is the rate of change of water depth on the hillslope surface,

$\frac{\partial Q}{\partial x}$ is the variation in discharge with distance down the hillslope,

r is water gained or lost per unit area.

The use of Darcy's equation for throughflow in combination with the Kinematic wave equation for surface runoff is discussed by Lee and Chang (2005), and used in a hillslope model for a mesoscale catchment in Taiwan.

Summary

- The approach required for hydrological modelling depends on the size of the catchment. For mesoscale basins such as the Mawddach, detailed rainfall distributions and detailed land surface characterisations are both required.
- The full hydrological analysis of a catchment may be carried out by two different approaches: the development of a single integrated model, or the linking of a series of specialist models to generate an integrated system. Specialist programs have been developed for particular stages of the hydrological cycle, including: rainfall modelling, hillslope runoff, groundwater, river routing, sediment transport and channel morphology, and estuary and coast tidal modelling.
- The main developments in hydrological modelling are favouring high resolution distributed systems, in which model parameters represent physically realistic and measurable properties of the catchment. Digital elevation data, typically with a spacing of 50m, can provide a grid basis for the model.
- Meteorological models, including MM5, have been successfully incorporated into hydrological systems and provide more accurate rainfall distributions than interpolation between widely spaced raingauge sites.
- An operational flood forecasting system for the Mawddach catchment requires a series of process modules: rainfall, hillslope runoff and throughflow, river routing, and overbank discharge. Additional modules may be incorporated for research purposes: groundwater flow, estuary tidal interactions, and river sediment transport.
- An automated system is proposed for the determination of soil hydrological properties, based on: Kirkby wetness index, geology, and vegetation.
- A hillslope model has been designed, in which infiltration and downslope throughflow are modelled by Darcy's equation and surface runoff is modelled by the Kinematic wave equation.
- In section 4.4, the hillslope model will be combined with the MM5 rainfall model, GSTARS river routing and River2D overbank discharge models, to produce an integrated flood forecasting system for the Mawddach catchment.