4.2 The Mawddach hillslope model

Design for the hillslope modelling program

The hillslope modelling software consists of two programs, the first to set up the catchment characteristics and the second to run the simulation (fig.4.15).

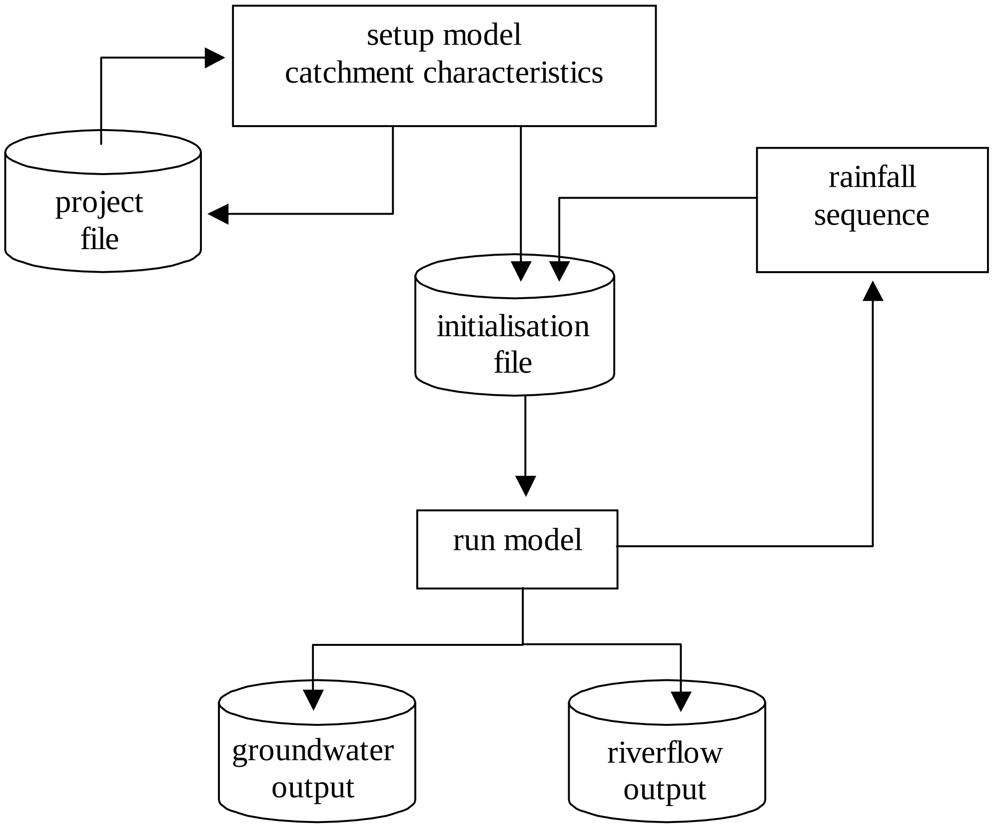


Figure 4.15: System flowchart for the Mawddach hillslope model

The setup program generates a project file combining the digital elevation data, drainage pattern, and soil and vegetation maps. The project file may be reloaded at a later time and edited, for example to simulate changes in vegetation for the catchment.

The project file is combined with a rainfall sequence derived from the MM5 meteorological model to produce the hillslope initialisation file. After running the program, data is output to the GSTARS package for river routing, and MODFLOW for groundwater modelling if required.

The initialisation file may be reconstructed using different rainfall sequences to simulate a series of storm events.

Modularisation of the hillslope setup program is illustrated in fig.4.16. The construction of the initialisation file proceeds by a series of stages, shown from left to right in the diagram.

The model for a sub-catchment is constructed on an Ordnance Survey basemap at 1:25000 scale (see Appendix A).

A digital elevation model provides altitude data on a 50m grid spacing for the entire region. This data is loaded into the program, and a rectangular area may be extracted to cover each sub-catchment.

The DEM extract is used to produce a contour map of the sub-catchment. Contouring is of value in checking the alignment of base maps with the digital elevation model, and to identify any anomolous points in the DEM.

The contouring algorithm divides each square of grid points using diagonals (fig.4.17), and the altitude at the mid point is obtained as a mean. A set of contour heights are chosen. Positions of contour intersections on grid square and diagonals can then be determined, and are linked by the contour lines.

The main applications of the digital elevation data within the hillslope model are in determining downslope water flow pathways, either through runoff, shallow subsurface stormflow, or in open stream channels.

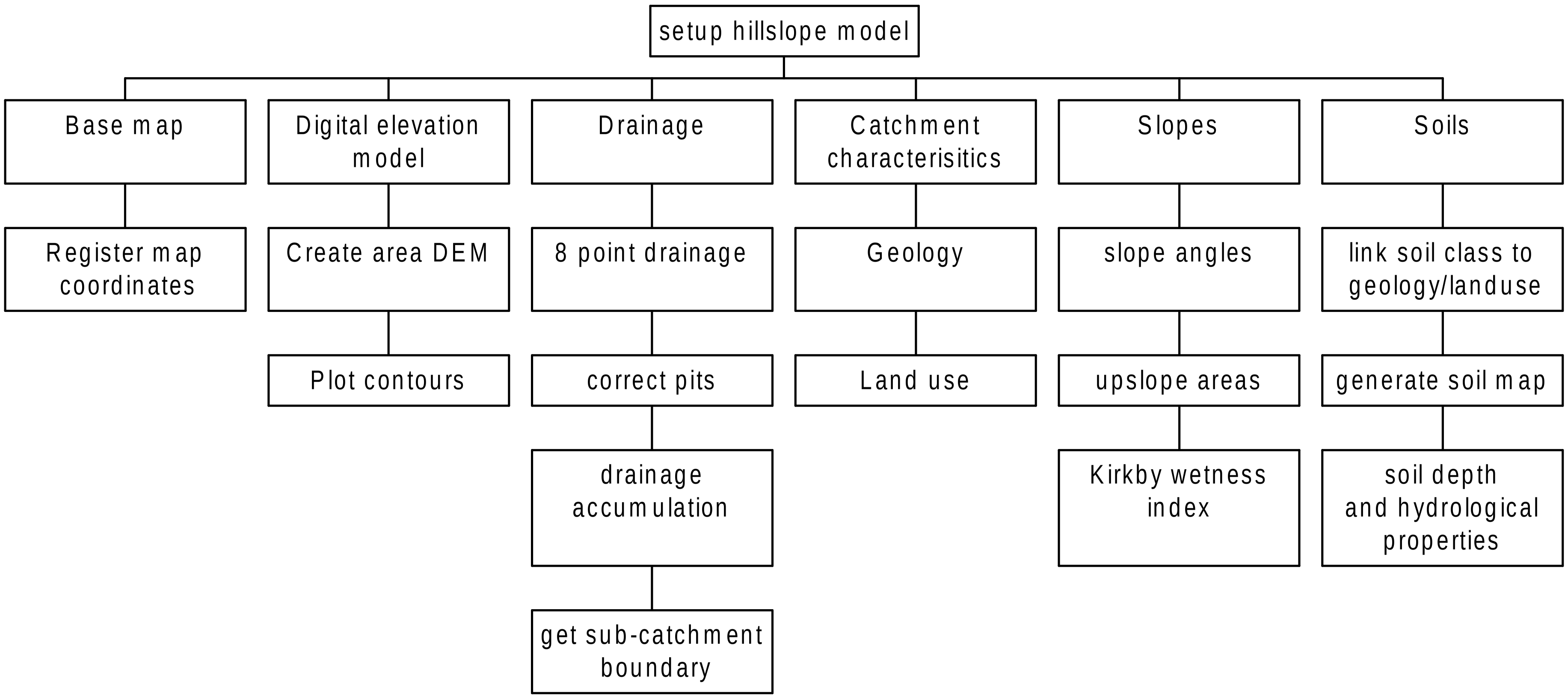


Figure 4.16: Modularisation of the hillslope setup program

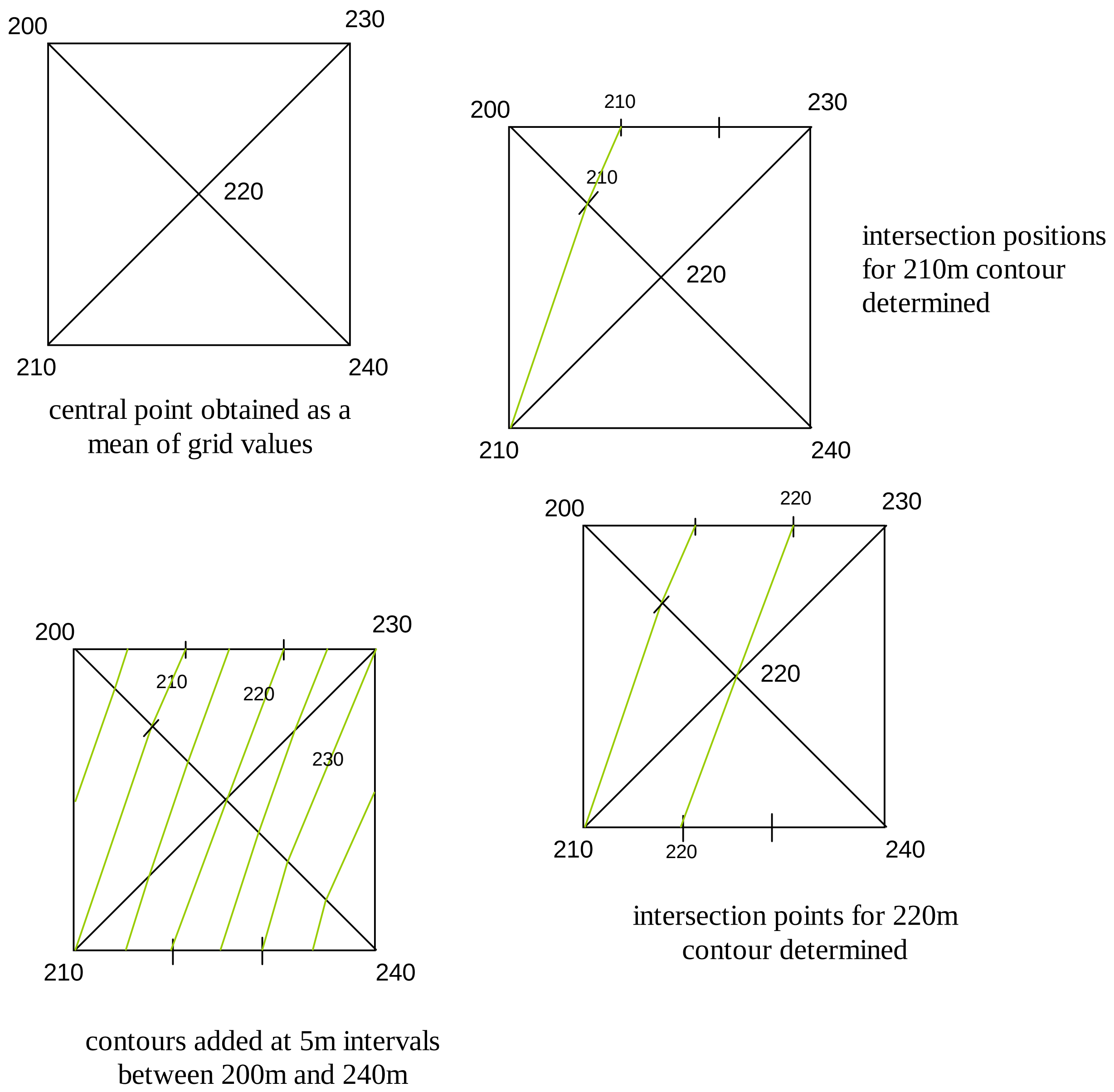


Figure 4.17: A demonstration of the contouring algorithm for digital elevation data

It is often the case that depressions or pits occur within the modelled surface, and represent physically unrealistic interruptions to water flow pathways. Pits typically appear along steep-sided V-shaped valleys as a result of the regularly spaced survey points of the 50m grid not always corresponding with the lowest points of the valley floor. Examples are seen in the uncorrected map of fig.4.18.

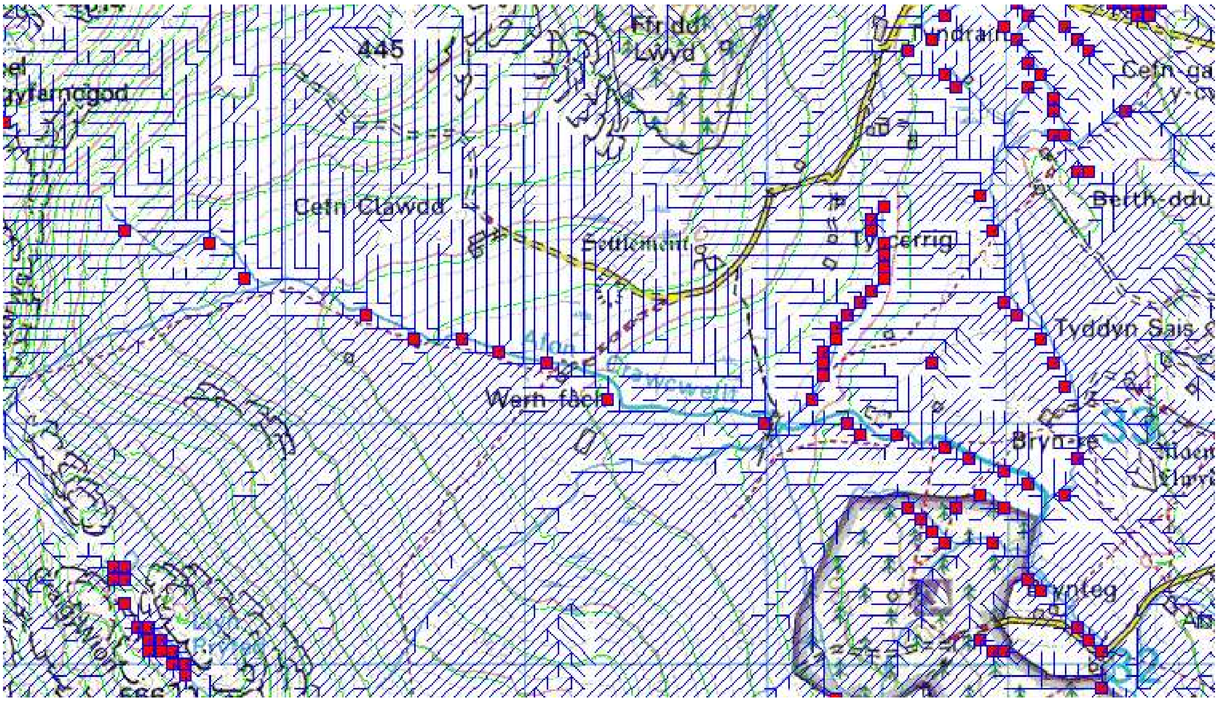


Figure 4.18: Pits in the uncorrected digital elevation model for Cefn Clawdd, Trawsfynydd. Surface drainage directions are indicated by blue lines

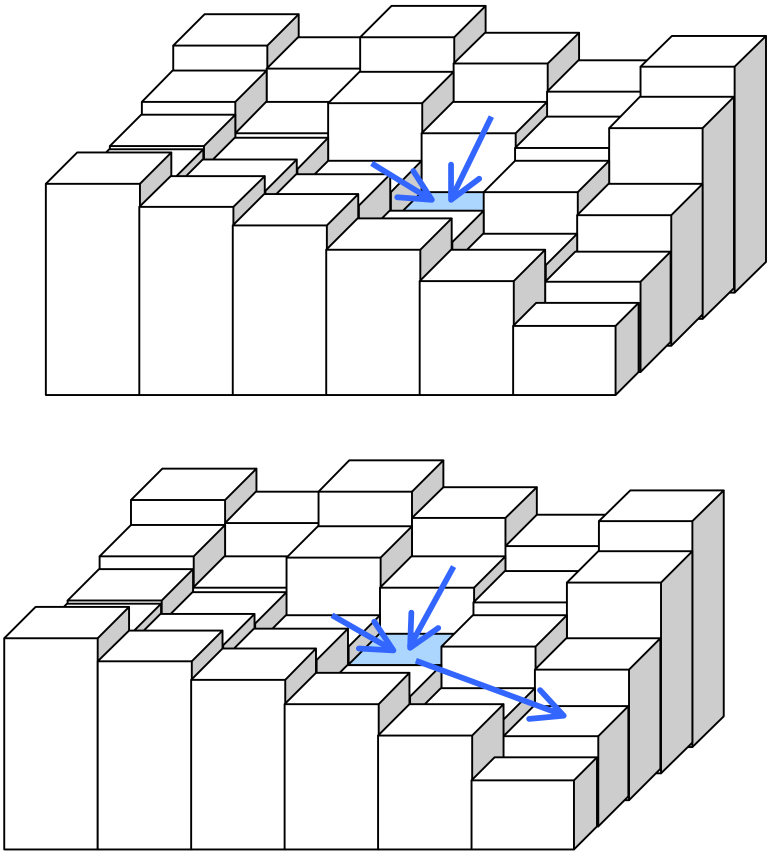


Figure 4.19: Occurrence of a pit in the digital elevation model, and its correction to restore downslope drainage

An algorithm within the hillslope program identifies cells which have drainage convergence, as in fig.4.19. A minimal increase in elevation is provided, so as to restore uninterrupted downslope flow.

The location of surface channels is determined by calculating the number of cells draining to each point of the sub-catchment. An open channel is assumed if this value exceeds a critical value. This value is chosen to generate headstream patterns as close as possible to those of the 1:25000 Ordnance Survey basemap (fig.4.20).

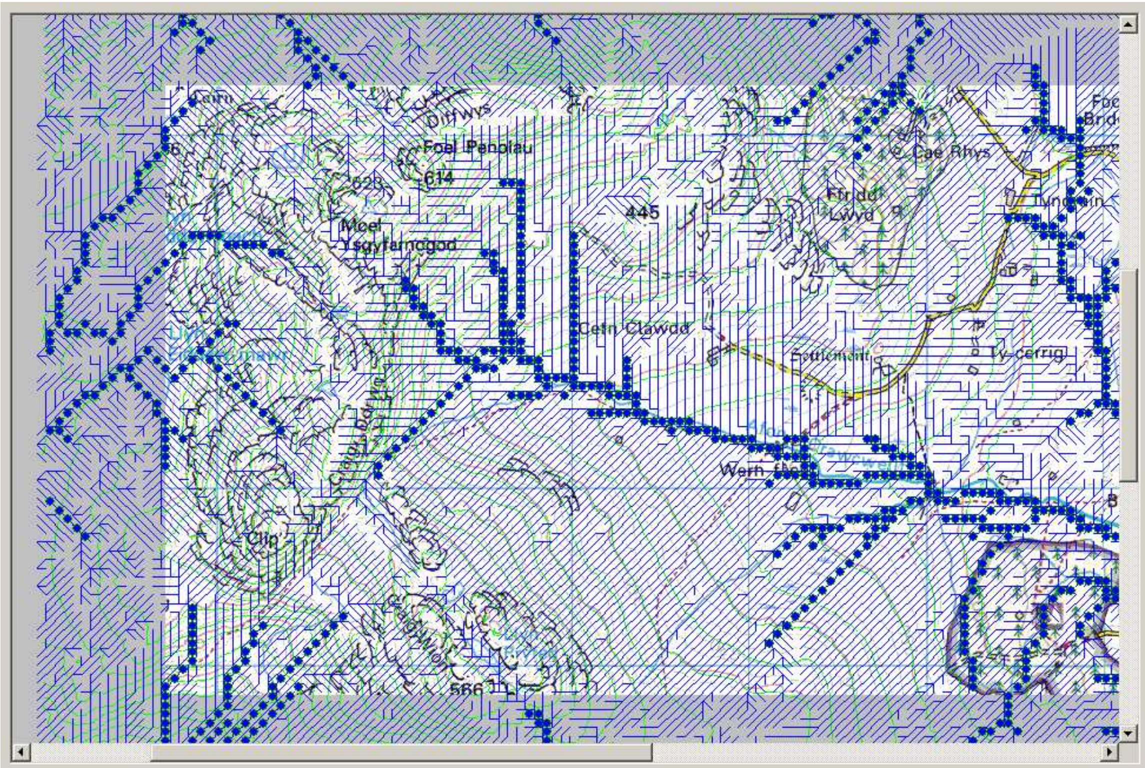


Figure 4.20: Designation of surface stream cells, Cefn Clawdd sub-catchment

A function is available within the hillslope model to determine the upslope contributing area which drains to any stream point, as demonstrated in fig.4.21. This function is used in determining sub-catchment boundaries, and also as a first stage in determining Kirkby wetness index.

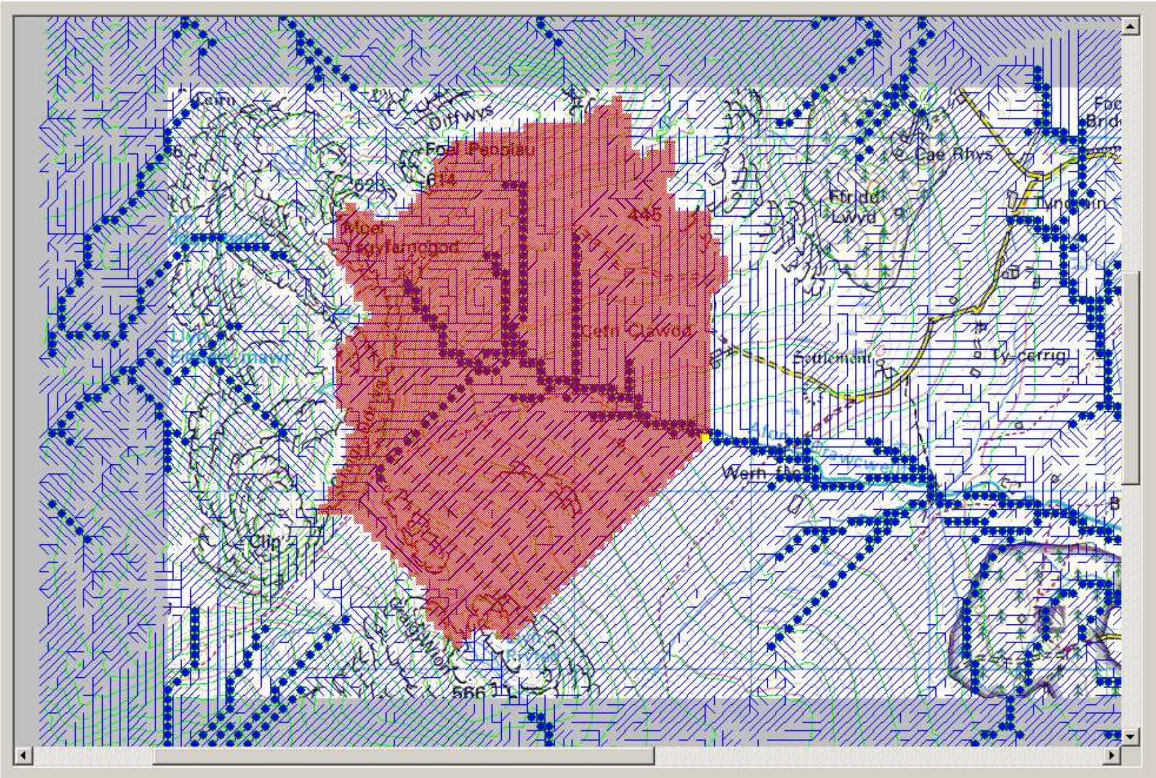


Figure 4.21: Example of the determination of upslope contributing area for a grid point (marked in yellow) within the Cefn Clawdd sub-catchment

Kirkby wetness index at any point on a hillslope is a function of the slope angle at that point, and also the upslope contributing area draining to that point. An algorithm calculates slope angle and upslope contributing area for each 50m cell of the sub-catchment, and combines these values to determine the Kirby wetness index for each cell. This data is subsequently used in the allocation of HOST soil classes.

The sequence for computing wetness index is illustrated by fig.4.22 for the Cefn Clawdd valley. Slope angle is greatest along the scarp face of the Rhinog mountains (coloured red/yellow), with gentler slopes in the floor of the glacial basin (blue). Upslope contributing areas increase towards the basin floor and river system (coloured yellow/red). The combination of these factors generates a Kirkby wetness index plot showing driest conditions (red) along the rocky valley sides, with wetness increasing towards the centre of the valley (blue). This is consistent with the distribution of natural vegetation from drier moorland on the mountain slopes, to wetter grassland, peat bog and mire on the floor of the valley.

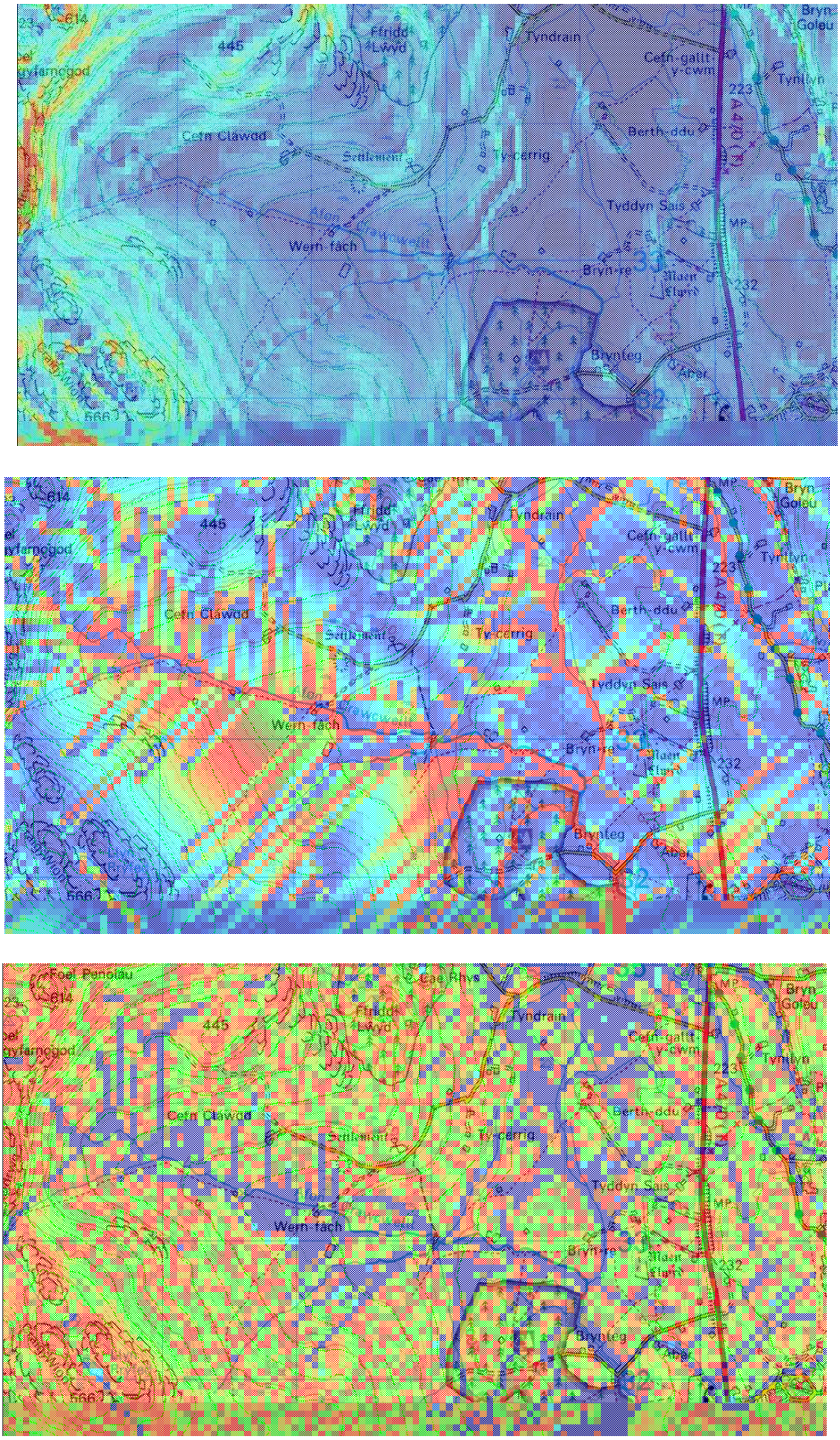


Figure 4.22: Sequence of stages in the calculation of Kirkby wetness index. (upper) slope angle, (middle) upslope contributing drainage area, (lower) wetness index. For explanation, see text.

The Mawddach integrated model uses the same set of sub-catchments as the HEC-1 model of chapter 3.1. For each sub-catchment, geology and land use maps have been prepared using Mapmaker software, then transferred to the SAGA GIS program in Arc View shape file format. Maps are then created on a 50m grid to correspond with the cells of the digital elevation model.

By combining Kirkby wetness index with geology and landuse, a grid of hydrologically similar soil zones is generated using the Institute of Hydrology HOST classification scheme, as outlined in section 4.1. The procedure for automated soil mapping for the example sub-catchment of Allt Lwyd is illustrated by figs 4.23-4.26:

The digitised geological map of the Allt Lwyd valley is shown in fig.4.23. The boundary between Cambrian sediments and Ordovician volcanics crosses the area from north to south, with the basal Ordovician beds marked by purple cross hatching. Ordovician acid ignimbrites form the high ground overlooking the Waen y Griafolen peat blanket bog, marked by yellow square shading. Much of the valley floor is occupied by glacial till, with a large area of alluvium marking the probable site of a glacial lake. The summit of Rhobell y big, to the south, is composed of basalts.

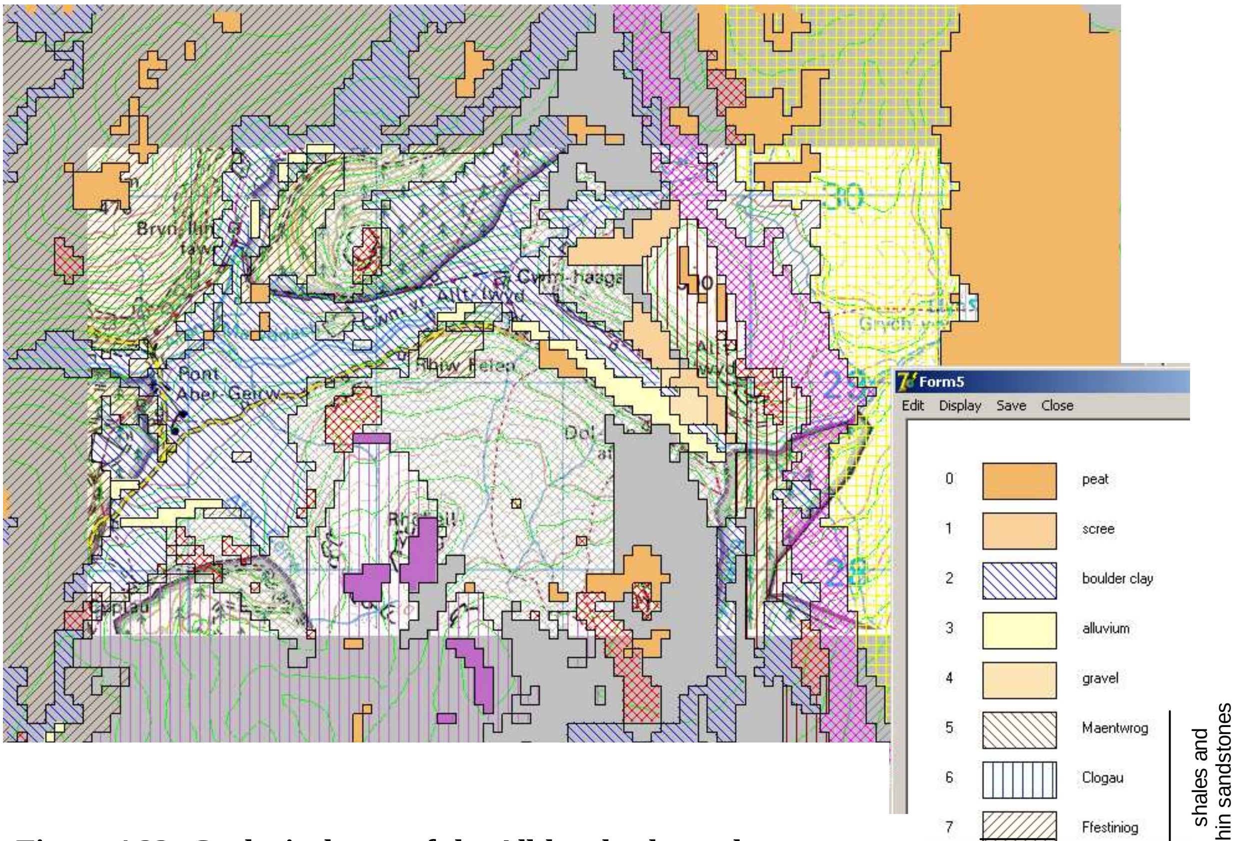
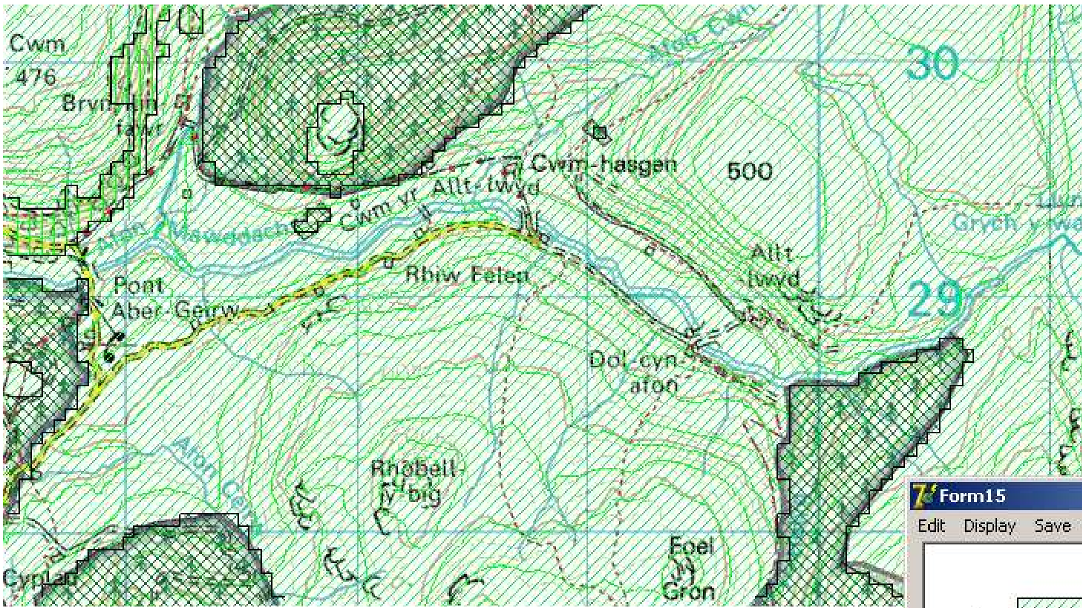


Figure 4.23: Geological map of the Alltlwyd sub-catchment

Fig.4.24 shows the digitised vegetation and land use map for the Allt Lwyd valley. The area is predominantly rough grassland, with several large coniferous forestry plantations.



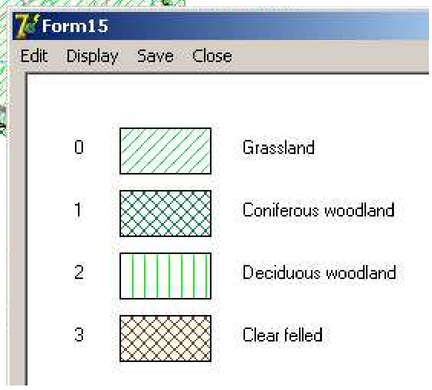


Figure 4.24: Land use map of the Alltlwyd sub-catchment

The Kirkby wetness index has been calculated and is displayed in fig. 4.25. Areas of predicted high water accumulation are shown in blue or green, with drier areas in yellow and red. The mapping algorithm predicts wet conditions along the valley floors and lower hillslopes, with drier summits and interfluves. Linear dry features are often seen alongside streams, reflecting the deeply incised nature of streams cut into glacial deposits to produce steep sided ravines.

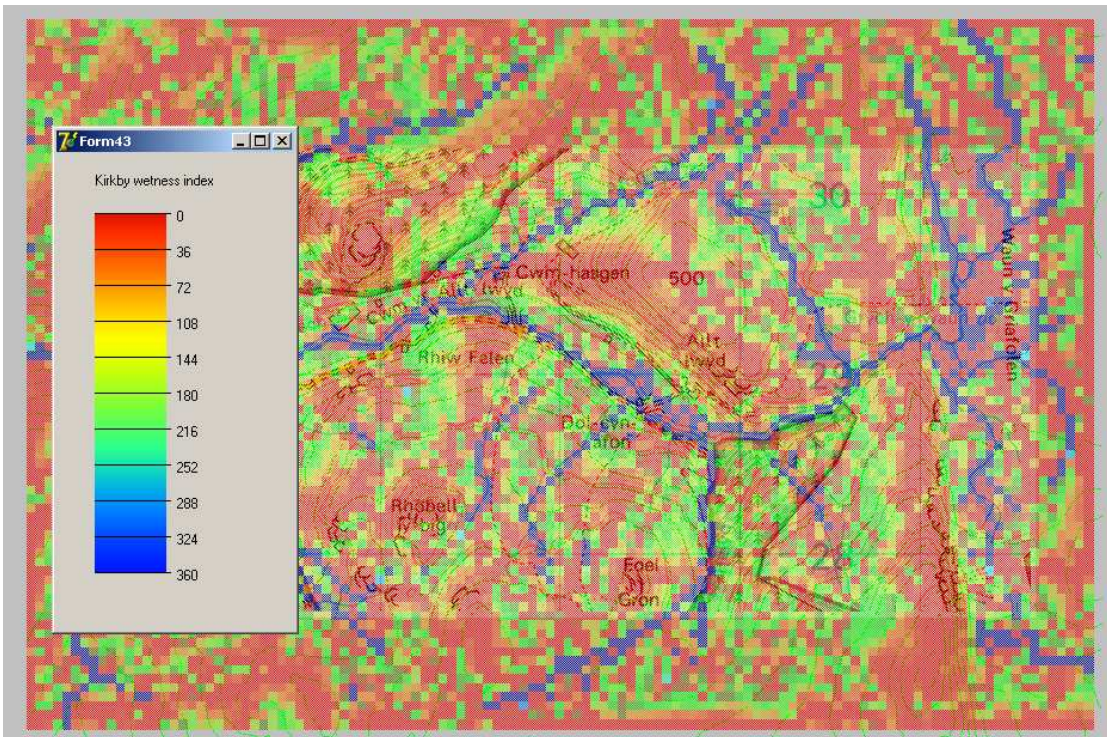


Figure 4.25: Kirkby wetness index plot for the Alltlwyd sub-catchment. Wettest areas shown in blue, damp in green, moderately dry in yellow, dry in red

By combining wetness index with geology/landuse, a grid of hydrologically similar soil zones has been generated using the Institute of Hydrology HOST classification scheme. Infiltration and run-off parameters can then be assigned from field evidence.

The mosaic of soils shown for the Allt Lwyd valley (fig.4.26) is consistent with field observations:

> Class 4 deep, slightly porous soil is developed on the glacial till, with Class 8 unconsolidated fine porous soil on the floodplain deposits. Class 5 unconsolidated soil with macropores occurs on the screes along the valley side.   The hard rocks of the Cambrian succession are covered by thin soils of Class 22, which may be gleyed in wetter zones to produce soils of Class 24. Greater infiltration is possible on the jointed and fractured igneous outcrops of the Ordovician succession, producing soil of Class 19. Peat of Class 29 occurs extensively across Waen y Griafolen, and in isolated pockets on the wetter mountain and valley sides.

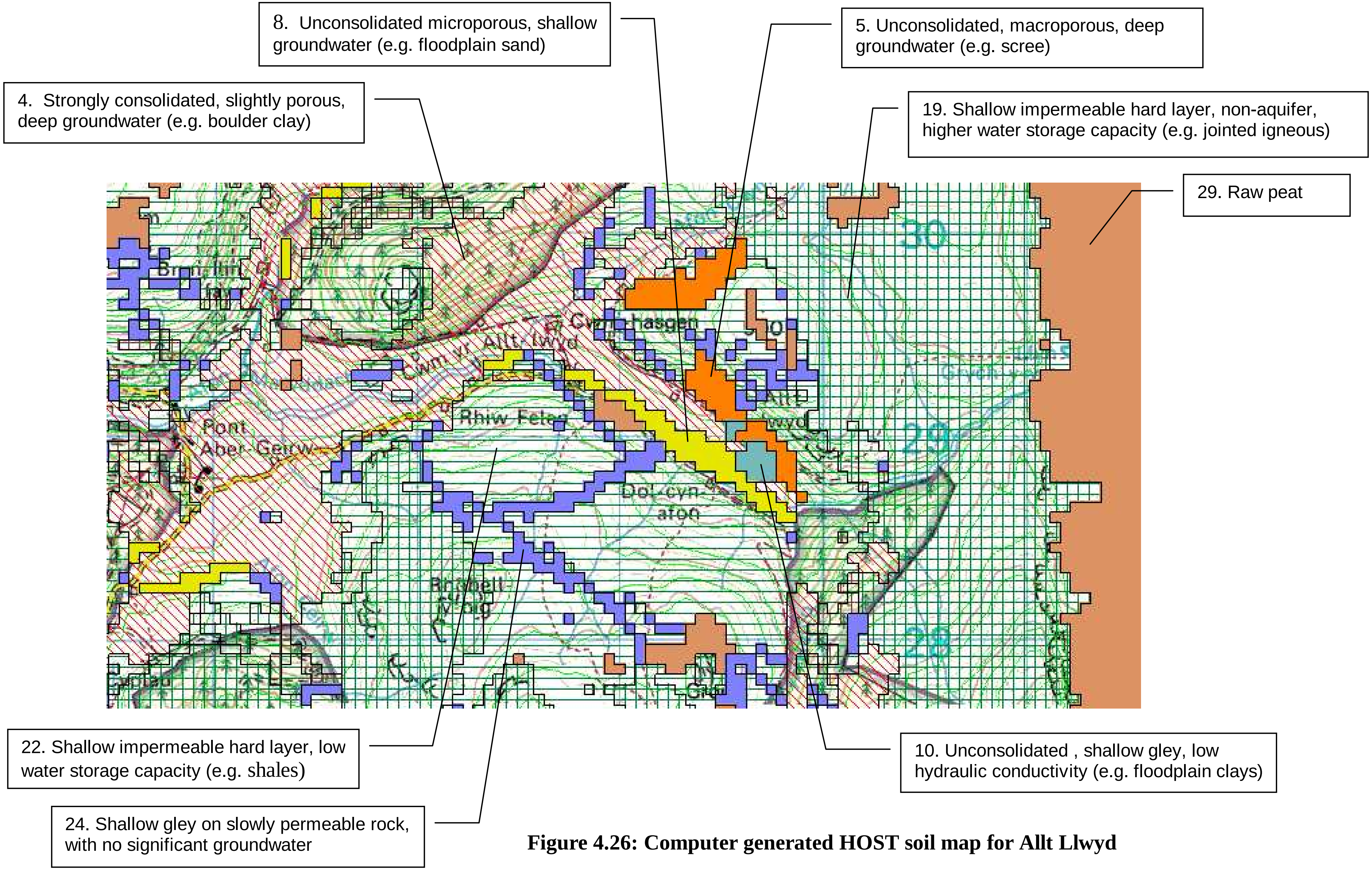


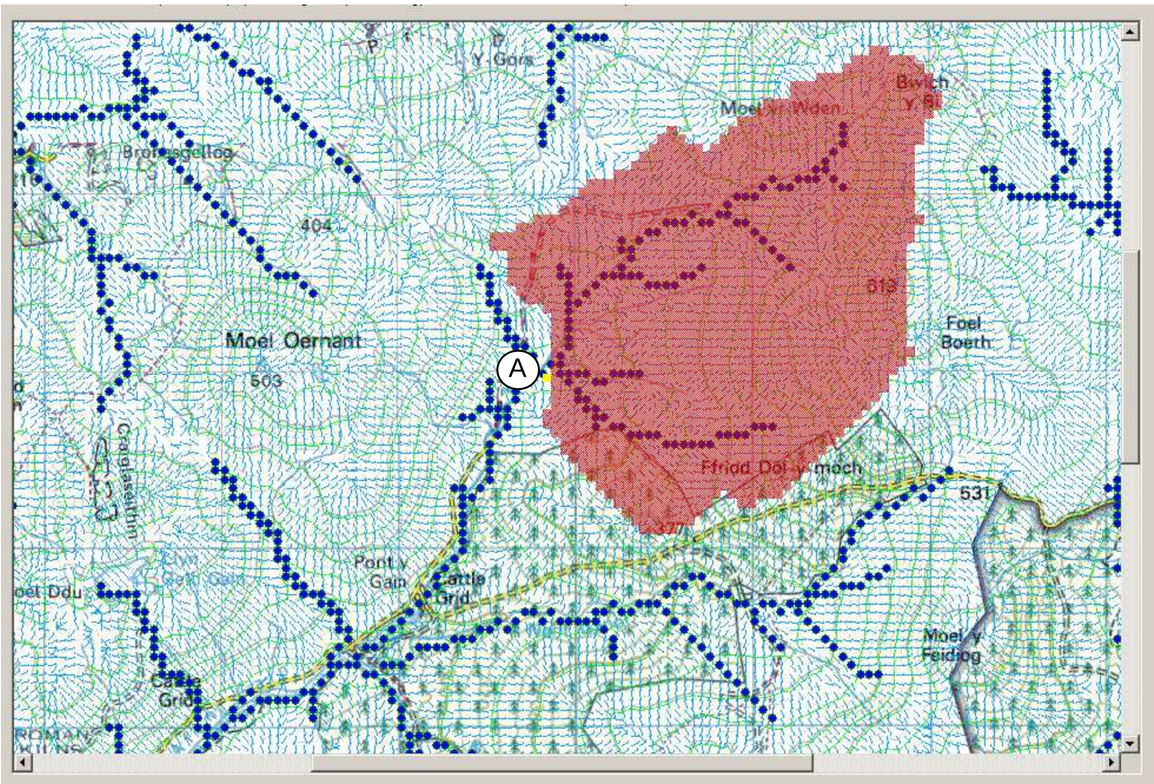
Figure 4.26: Computer generated HOST soil map for Allt Llwyd

After generation of the soil map, typical textures can be allocated for topsoil and subsoil soil zones, along with typical soil thickness (fig.4.27). These characteristics will be used later in the calculation of hillslope infiltration and throughflow volumes.

HOST class	description	topsoil texture	topsoil depth (m)	subsoil texture	subsoil depth (m)
3	Weakly consolidated, macroporous, deep groundwater (e.g. old gravels)	Coarse	1.2	Coarse	0.8
4	Strongly consolidated, slightly porous, deep groundwater (e.g. boulder clay)	Medium	0.9	Medium	0.8
5	Unconsolidated, macroporous, deep groundwater (e.g. scree)	Coarse	1.6	Coarse	1.0
6	Unconsolidated, microporous, deep groundwater (e.g. dune sand)	Fine	1.2	Fine	0.8
7	Unconsolidated, macroporous, shallow groundwater (e.g. river gravel)	Coarse	0.6	Coarse	0.4
8	Unconsolidated, microporous, shallow groundwater (e.g. floodplain sand)	Medium fine	0.7	Medium fine	0.4
9	Unconsolidated, shallow gley, low hydraulic conductivity (e.g. floodplain clays	Fine	0.6	Fine	0.6
10	Unconsolidated, shallow gley, high hydraulic conductivity (e.g. marsh sand)	Medium	0.8	Medium	0.6
11	Peat, shallow groundwater, drained	Organic	0.6	Organic	0.6
12	Peat, shallow groundwater, undrained	Organic	0.6	Organic	0.6
13	Mineral soil, shallow impermeable layer, deep groundwater (occasionally satur	Medium fine	0.3	Medium fine	0.4
14	Mineral soil, shallow gleyed layer, normally deep groundwater (seasonally satu	Medium fine	0.3	Medium fine	0.4
15	Peat, deep groundwater (on fast draining bedrock)	Organic	0.5	Medium	0.2
16	Slowly permeable, no significant groundwater (e.g. compact shales)	Medium	0.4	Medium	0.2
17	Impermeable, hard rock, no significant groundwater (e.g. compact mudstone	Medium	0.3	Medium	0.2
18	Shallow slowly permeable layer, non-aquifer, higher water storage capacity	Medium fine	0.4	Medium fine	0.3
19	Shallow impermeable hard layer, non-aquifer, higher water storage capacity (e	Medium fine	0.3	Medium fine	0.3
20	Shallow impermeable soft layer, non-aquifer, higher water storage capacity (e.	Medium fine	0.3	Medium fine	0.3
21	Shallow slowly permeable layer, low water storage capacity	Medium fine	0.4	Medium fine	0.3
22	Shallow impermeable hard layer, low water storage capacity (e.g. shales)	Medium fine	0.4	Medium fine	0.3
23	Shallow impermeable soft layer, low water storage capacity (e.g. clay)	Medium fine	0.3	Medium	0.3
24	Shallow gley on slowly permeable rock with no significant groundwater	Medium	0.3	Medium	0.3
25	Shallow gley on impermeable rock with no significant groundwater	Medium	0.3	Medium	0.3
26	Peat on slowly permeable rock with no significant groundwater	Organic	0.5	Fine	0.1
27	Peat on impermeable hard rock with no significant groundwater	Organic	0.5	Very fine	0.1
28	Eroded peat	Organic	0.5	Organic	1.0
29	Raw peat	Organic	1.0	Organic	1.0

Figure 4.27: Look-up table relating HOST soil class to soil depth and texture

In order to set up an initialisation file, it is necessary to determine the sub-catchment boundary. The program provides functions for including or excluding areas upstream of specified points in the river system (fig.4.28).



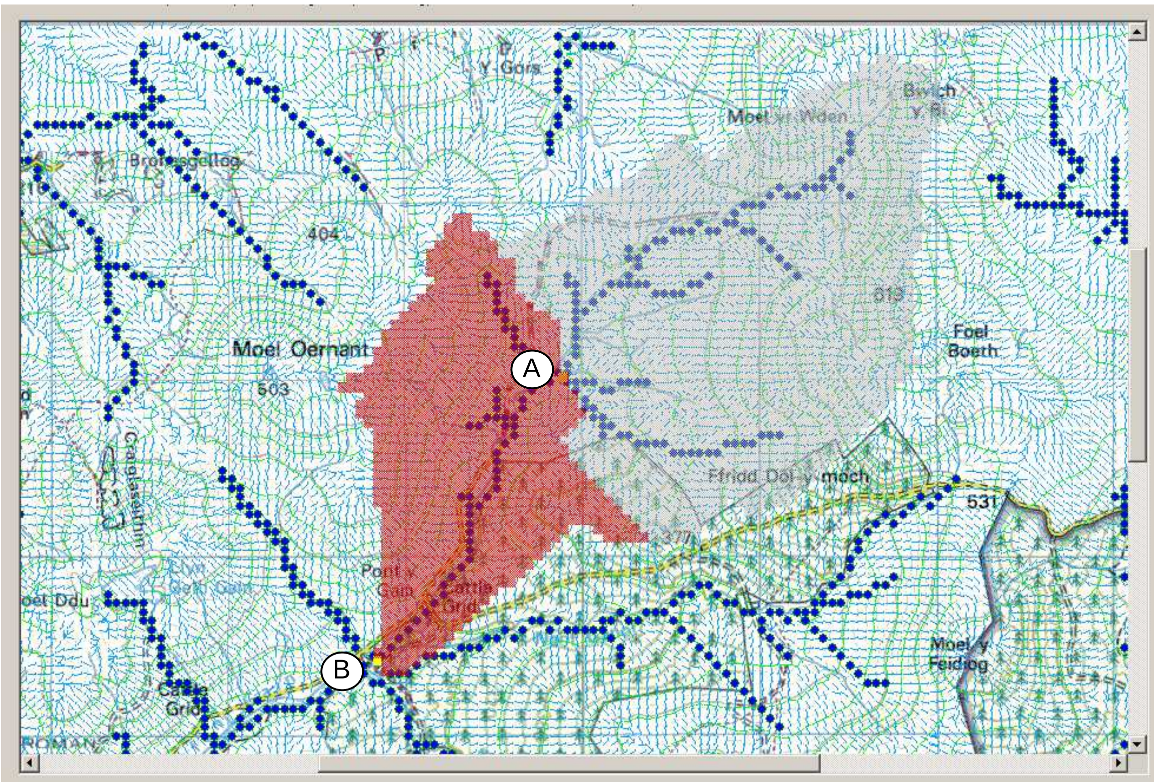


Figure 4.28: Determination of sub-catchment boundaries. (above) Sub-catchment upstream of point A. (below) Sub-catchment upstream of point B, excluding the area upstream of A.

Creation of an initialisation file

During the stages of setting up the catchment characteristics, a project file may be saved for subsequent editing and for use in creating model initialisation files. The project file contains links to:

- the Ordnance survey base map
- the sub-catchment digital elevation model
- digitised geology and landuse maps
- Kirkby wetness index array for the sub-catchment
- HOST soil distribution array
- drainage pattern and sub-catchment boundary

Before running the hillslope model, a rainfall sequence must be supplied. Sequences can be prepared from the output files of the MM5 meteorological program.

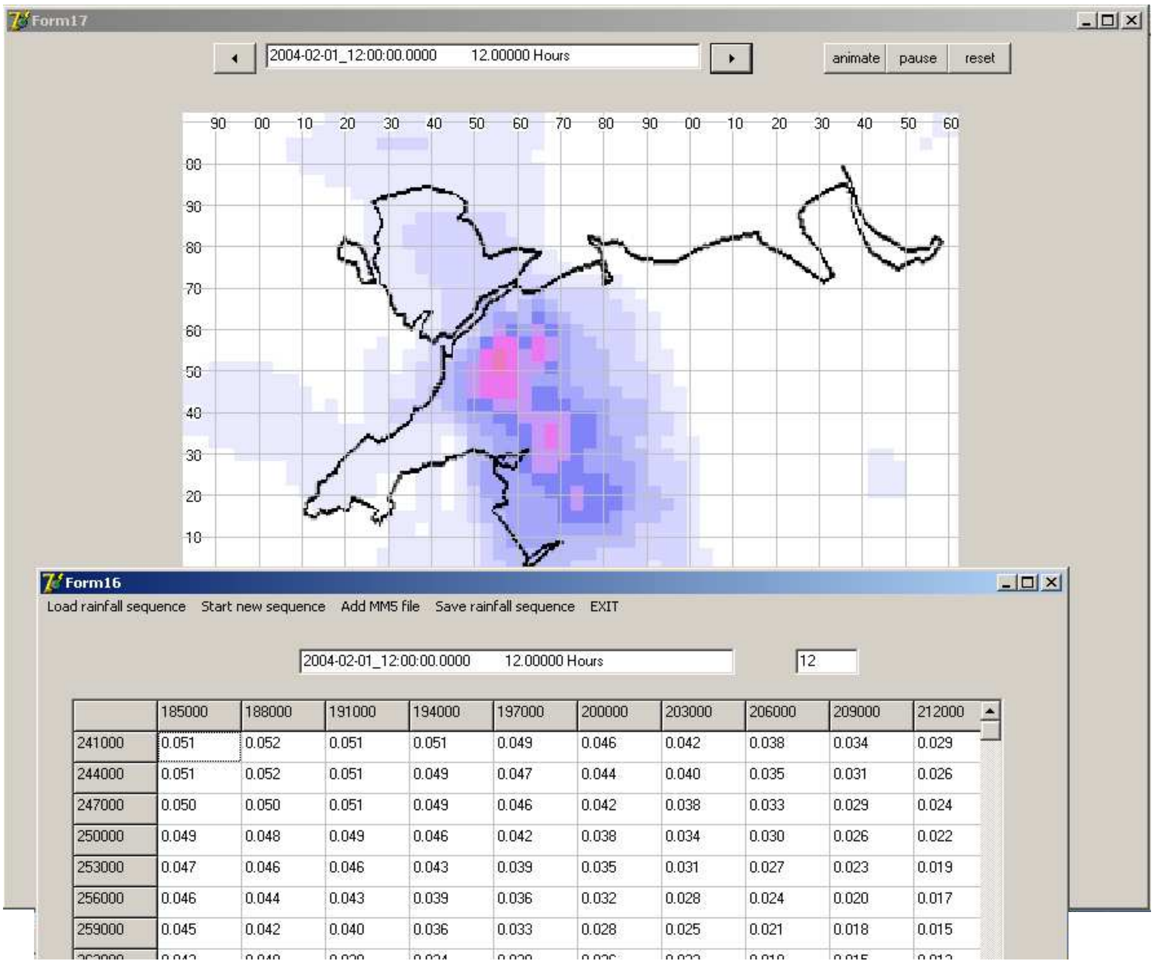


Figure 4.29: Example time frame from the storm rainfall sequence of February 2004, specified on a 1km grid. Rainfall shown in cm/hour.

A utility program has been written in FORTRAN90 to convert MM5 files to ASCII format for input to the hillslope model. Aspects of FORTRAN programming are covered by Chapman(2004). Rainfall sequences are generated on a 1km grid scale (fig.4.29). Grid squares covering the sub-catchment provide data for use in the hillslope model.

All information needed to run a hillslope simulation is now in place, and the model initialisation file can be created. Data arrays are displayed, and may then be compiled into the initialisation file. This comprises:

- slope directions and angles
- soil hydrological parameters
- sub-catchment boundary definition
- rainfall sequence

Subsoil initial saturation | Topsoil residual stored water ratio | Subsoil residual stored water ratio | Topsoil porosity
Rainfall | Topsoil depth | Topsoil saturated conductivity | Subsoil depth | Subsoil saturated conductivity | Topsoil initial saturation
Subsoil porosity | Slope angle | Drainage direction | Catchment boundary | Topsoil M | Subsoil M

	272000	272050	272100	272150	272200	272250	272300	272350	272400	2724
330000	15.87	17.8	18.66	13.66	16.76	22.73	22.29	19.43	9.52	5.27
329950	16.72	15.96	18.13	15.46	18.27	22.1	22.35	15.7	9.06	6.22
329900	14.58	16	13.72	17.75	18.11	21.34	21.76	14.98	7.47	5.17
329850	16.69	15.69	10.19	16.07	19.08	19.47	21.47	16.59	5.12	8.15
329800	17.99	14.01	11.02	10.27	19	17.79	22.14	17.48	5.94	10.1
329750	17.78	13.94	11.59	7.46	14.65	17.79	22.1	18.33	9.71	10.3
329700	17.06	13.33	11.27	7.19	9.91	16.54	21.11	16.49	6.14	14.5
329650	15.25	12.95	9.62	6.7	8.49	13.5	19.64	19.73	8.92	16.9
329600	14.29	13.46	8.56	5.69	8.26	12.96	15.63	20.24	11.56	15.1
329550	15.96	12.86	10.36	5.89	8.76	12.67	10.93	16.84	15.57	16.5
329500	15.7	10.78	12.49	8.7	9.47	11.66	8.25	8.13	13.21	18.61
329450	15.03	6.69	10.61	9.79	8.64	12.01	7.84	10.02	18.17	22.7
329400	15.1	6.89	9.88	9.37	6.09	14.23	11.33	6.68	16.5	18.9
329350	14.11	10.55	10.71	9.96	8.32	12.83	14.42	16.27	17.16	19.6
329300	12.46	10.94	10.51	11.58	10.68	11.92	17.9	19.41	11.75	17.7
329250	11.36	10.87	7.26	9.54	10.62	12.24	16.79	19.28	19.37	20.2

Figure 4.30: Set of data arrays on a 50m grid created for the sub-catchment, and used for initialisation of the hillslope model run. Slope angle (degrees) is shown.

Running the hillslope model

The initialisation file is loaded and the simulation may be run. The program moves through 15 minute time steps, and may be paused at any time to generate output.

Output options include

- ***maps***, showing hydrological responses for the sub-catchment: surface runoff, throughflow, infiltration to bedrock.
- ***block diagrams,*** showing hydrological data in a three-dimensional format. The block diagram may be rotated and zoomed in on areas of interest.
- ***cell data,*** showing the hydrological state of any particular cell within the sub-catchment for the current time interval.

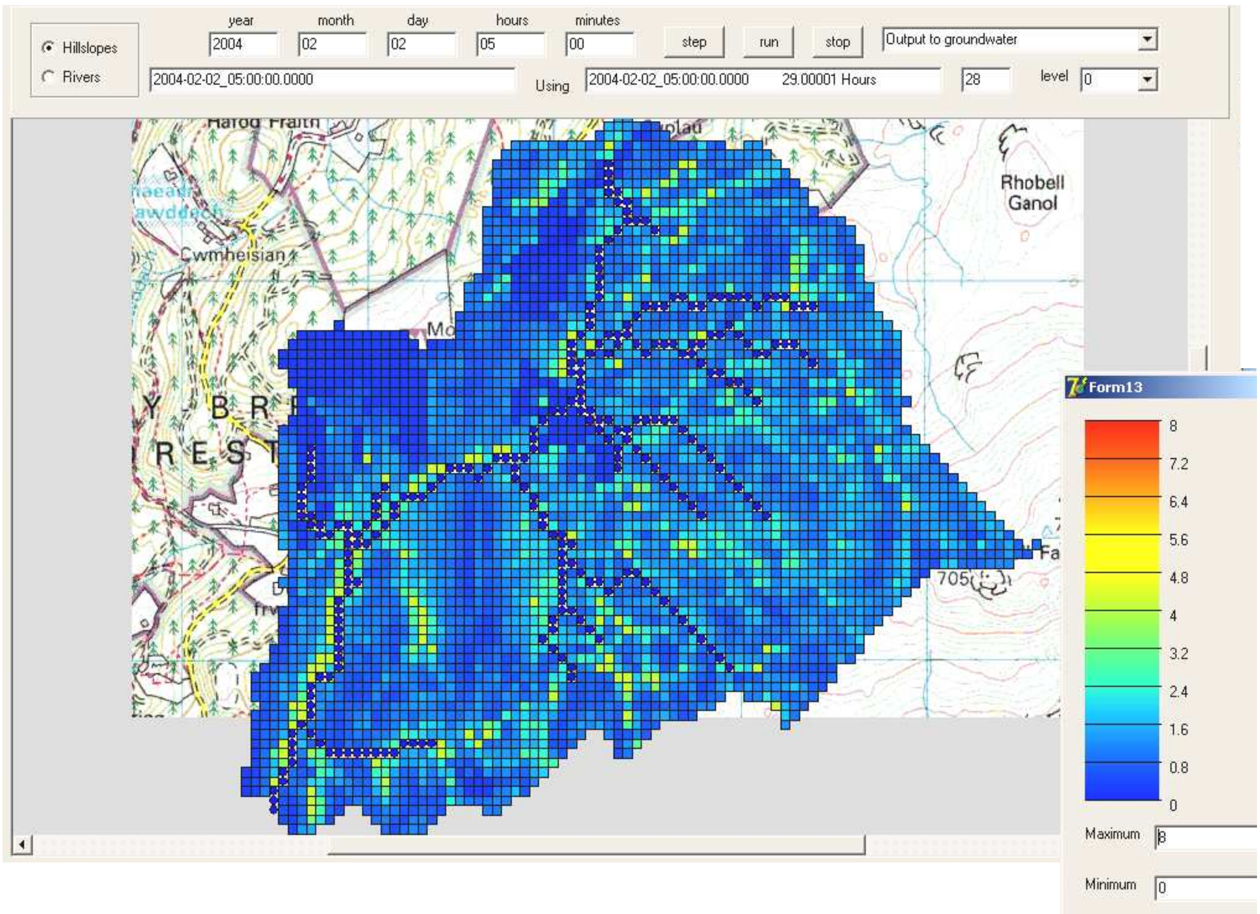


Figure 4.31: Output map showing infiltration to groundwater within the Afon Wen sub-catchment during the February 2004 storm event (m^3/hour per 50m grid square)

An example of cell output is shown in fig.4.32, and illustrates the operation of the model:

> During each time interval, rainfall is added to the surface of the grid cell. Soil water may also enter layers of the cell through downslope throughflow or surface runoff from one or more adjacent cells.
>
> Hydrological conductivity is computed according to the level of saturation of soil layers within the grid cell. Water is transmitted downwards, and may infiltrate to groundwater store from the lowest subsoil layer.
>
> Lateral flow of soil water is computed. Throughflow is partitioned to a maximum of two downslope cells.
>
> If soil water is present in excess of the storage capacity of the cell, the additional water is released as surface runoff to downslope cells.

Water balance is calculated for the cell, as a check on conservation of mass.

Output to groundwater storage is recorded in an array for each time interval, and may be used as input to the MODFLOW model.

Volumes of water arriving at a river channel cell as surface runoff or soil throughflow is recorded in an array for each time interval, and provides an input to river routing within the sub-catchment. Outflow from the sub-catchment is recorded, and passed to the GSTARS program for further routing downstream through the whole river system.

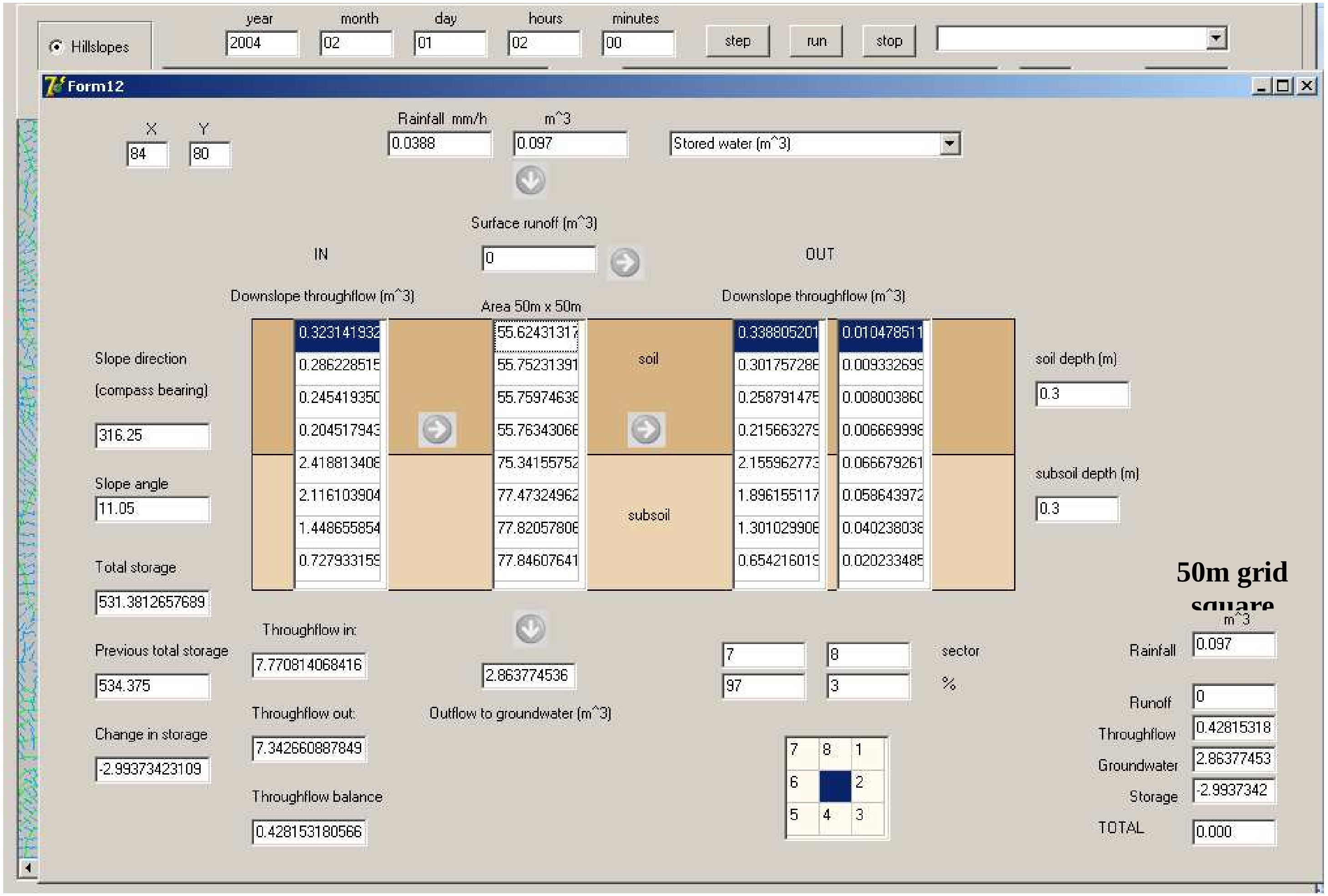


Figure 4.32: Hydrological output for a cell of the hillslope model

Summary

- The hillslope model is composed of two software programs, the first to set up sub-catchment characteristics, and the second to carry out the hydrological simulation.
- The program uses an Ordnance Survey 1:25000 base map and a digital elevation model on a 50m grid.
- Geometrical functions determine the drainage pattern and boundary for the sub-catchment.
- Kirkby wetness index is calculated for each grid square, based on slope angle and upslope contributing drainage area.
- Digital maps of geology and vegetation/land use are input, and combined with the Kirkby wetness index to generate a soil map based on HOST soil classes.
- The host classification allows hydrological parameters to be allocated to the topsoil and subsoil layers of each cell, and for soil depth and texture to be estimated.
- Rainfall sequences are imported from the MM5 meteorological program, and may be combined with sub-catchment surface characteristics to produce an initialisation file for the hillslope hydrological simulation.
- The hillslope model can generate output in the form of maps, block diagrams, and hydrological response data for individual grid cells.
- Water flow data may be output from the hillslope model to the MODFLOW groundwater model, and to the GSTARS river routing model.