SHETRAN Version 4

Data Requirements, Data Processing and Parameter Values

Executive Summary

This report describes the data required for a SHETRAN simulation this includes spatial data, physical property data and meteorological data. Methods for obtaining and processing the data, together with relevant references, are given in the report. Libraries of suitable parameter values are also given.

Note, this report needs some work on it

Contents

Section 1 - Summary of data types

1.1 Spatial Data

Type of data	Data sources	Processing method	References
Catchment Geometry	Digital elevation models	Use GIS and position of outlet. Can be used in SHETRAN Windows	Jenson and Domingue (1988)
	Maps	By hand analysing the contours	
Ground Surface Elevations	Digital elevation models e.g., ~1km resolution data from USGS web site	GIS. Can be used in SHETRAN Windows	
	Maps	By hand	
River Network	Vector maps of river network	By hand	
	Digital elevation models	Use SHETRAN Windows to obtain an approximate river network from flow accummulation of DEM.	Tarboton et al. (1991)
	Maps	By hand	
River Network Elevations	Digital elevation models	SHETRAN Windows	
	Maps	By hand	
Rainfall /meteorological station distribution	Position of each rainfall/ meteorological station	Thiessen Polygon or Isohyets to specify distribution	Shaw (1994)

Land cover distribution	Digital distribution	GIS and SHETRAN Windows	
	Aerial photography	By hand	
	Satellite imagery	By hand	
	Maps	By hand	
Soil distribution and depths	Digital distribution	GIS and SHETRAN Windows	
	Soil maps	By hand	
Geology	Digital distribution	GIS	
	Hydrogeological maps	By hand	
	Borehole logs	By hand	
	Geophysics to define extent, thickness and connectivity of aquifers /aquitards	By hand	

1.2 Physical Properties

1.2.1 Soil Properties

Specific Property	Data Sources	Processing Method	References
Porosity	Measured or estimated using soil texture size distribution as below		Freeze and Cherry (1979)
Soil Moisture Characteristic Function (ψ,θ)	More than 5 pairs of $\psi-\theta$ values available	Use $\psi-\theta$ values or convert to van Genuchten parameters (Fortran program available)	For details on measuring see Ragab and Cooper (1990). To convert measurements see van Genuchten (1980)
	Soil texture size distribution (e.g. %sand, %silt, %clay)	Saxton equation to obtain $\psi-\theta$ values (Fortran program available). Use $\psi-\theta$ values or convert to van Genuchten parameters	Saxton et al. (1986)
	Descriptive soil classification (e.g., sandy loam)	Library of soil parameters. See Appendix A	
Saturated Conductivity	Measured and literature values		Freeze and Cherry (1979)
	Empirical methods based on descriptive soil classification (e.g., sandy loam)	Library of soil parameters. See Appendix A	Rawls et al. (1982)
Conductivity Function (θ,K) Relationships	More than 5 pairs of $\theta-$K values available	Use either $\theta-$K values, van Genuchten parameters or Averjanov function	For details on measuring of $\theta-$ K values see Ragab and Cooper (1990). For details on the Averjanov function see Maulem (1978)
	Soil texture size distribution (e.g. %sand, %silt, %clay)	Use van Genuchten parameters or the Averjanov function	
	Descriptive soil classification (e.g., sandy loam)	Library of soil parameters. See Appendix A	

Specific Storativity	Measured or estimated from aquifer proerties		Younger (1993)

1.2.2 Vegetation Properties

Specific Property	**Data Sources**	**Processing Method**	**References**
Vegetation Cover Indicies	Measurement		Burman and Pochop (1994)
	Standard vegetation types	Adapt library of standard vegetation type. See Appendix B1	
Canopy Storage	Measurement		Klassen et al. (1998)
	Literature values		Rutter (1975)
	Standard vegetation types	Adapt library of standard vegetation type. See Appendix B1	
Drainage Parameters	Literature values for Rutter model drainage parameters		Dunn and Mackay (1995)
	Standard vegetation types	Adapt library of standard vegetation type. See Appendix B1	
Root Density Function	Measurement and literature values		Gregory (1988)
	Standard vegetation types	Adapt library of standard vegetation type. See Appendix B2	
Evapotranspiratio n Parameters -	Aerodynamic and canopy resistance – measurments and literature values		Burman and Pochop (1994)
	Aerodynamic and canopy resistance values - SHETRAN simulations		Dunn and Mackay (1995)
	Actual / potential evapotranspiration ratio - literature values		Shuttleworth (1993)
	Actual / potential evapotranspiration ratio – standard vegetation types	Adapt library of standard vegetation type. See Appendix B3	

1.2.3 Overland flow / Channel parameters

Specific Property	Data Sources	Processing Method	References
Channel cross-sections	Measure		
Roughness parameters in river channel	Literature values	Strickler values (inverse of Manning's n)	Chow (1973)
Roughness parameters on land	Literature values	Strickler values (inverse of Manning's n)	Engman (1986)

1.3 Meteorological Data

Data sources	Processing method	References
Full meteorological data at regular time intervals including: rainfall, net radiation, air temperature, humidity and wind speed	Use meteorological data file (MED file).	
	Calculate potential evaporation using Penman equation and use breakpoint rainfall file (PRD) and breakpoint evaporation file (EPD)	
Hourly rainfall and potential evapotranspiration data	Use breakpoint rainfall file (PRD) and breakpoint evaporation file (EPD)	
Daily rainfall and potential evapotranspiration data	Disagreegate rainfall data. Use breakpoint rainfall file (PRD) and breakpoint evaporation file (EPD)	
Rainfall and air temperature data	Use Blaney-Criddle equation to calculate potential evaporation from air temperature for breakpoint evaporation file (EPD) and use breakpoint rainfall file (PRD). Fortran program available	Burman and Pochop (1994)

1.4 Individual parameters

Parameter	Data Sources	Processing Method	References
Basic timestep		Normally 1 or 2 hours	
Maximum river discharge		Set to be slightly larger than biggest possible flow.	
Weir locations, sill elevation and coefficients	Weir design details		

1.5 Calibration / Validation data

Data Sources	Specific Data	Processing Method	References
River and spring discharges for calibration or validation	Water level measurements	Develop a stage/ discharge relationship	Parkin et al. (1996)
Water table and piezometric levels	Dip well measurements		Parkin et al. (1999), Birkinshaw and Ewen (2000)
Soil moisture or tension data			Bathurst et al. (2004)

1.6 Initial conditions

Data Type	Specific Property	Processing Method	References
Depth of water -grid squares		Measured. Normally set to zero	
Depth of water – channels		Measured. Normally set to zero	
Initial subsurface conditions	Equilibrium profile	Measured or estimated.	
	Phreatic surface elevations	Measured or obtained from an initial simulation using an equilibrium profile.	
	Potentials in every cell	Obtained from an initial simulation using phreatic surface elevation or an equilibrium profile.	

1.7 Boundary data (optional)

Type of data	Specific Data	Processing Method	References
Well data		Measured	
Spring data		Measured	
Overland flow in/out of the catchment	Flow data.	Measured	
	Head data	Measured	
	Polynomial data	Measured	
Lateral subsurface flow in/out of the catchment	Flow data	Measured	
	Head data	Measured	
	Head gradient data	Measured	
Flow in/out of the base of the catchment	Flow data	Measured	
	Head data	Measured	
	Free drainage		

1.8 Snowmelt (optional)

Type of data	Specific Data	Processing Method	References
Snowmelt data	Degree-day factor	Degree-day parameter plus specific gravity of the snow	Morris (1985)
	Energy budget data	Full meteorological data (see 5.1)	Kuusisto (1986)
Initial snowpack depth		Measured	
Initial snowpack density		Measured	
Measured outlet discharge for calibration and validation	See 7.1		Bathurst and Cooley (1996)
Measured snow depth for calibration and validation	Spatial variable values over the catchment	Measured	

Section 2 - Spatial Data

2.1 Catchment Geometry

2.1.1 General

The catchment geometry is specified in SHETRAN by defining a grid for the catchment. Those elements within the catchment have a value 1 or those outside the boundary take the value of 0.

Note: catchment is defined in the loosest sense of the word. Often SHETRAN simulates an actual catchment with clearly defined borders. Sometimes only part of an actual catchment is simulated, e.g. a hillslope or a simulation focusing on groundwater flows in part of a catchment. In these cases there will be a variety of surface and subsurface inflows and outflows from the catchment which must be also defined (see Section 9).

2.1.2 Processing method

If a Digital Elevation Model (DEM) is available for a catchment this can easily be used with a GIS to obtain the catchment geometry, which can then be used directly in SHETRAN winodws. For example,

- If necessary increase the grid size of the DEM so it is the same as the required SHETRAN grid size
- Fill in the sinks (areas in the DEM surrounded by higher land from which the water cannot drain) in the catchment and calculate the flow direction
- Obtain the catchment geometry (using the **flow direction** and the position of the outlet.)
- Convert to ASCII format
- Use catchment geometry with DEM data of the same grid size in SHETRAN Winodws.

See Jenson and Domingue (1988) for details on removing sinks from a DEM and then processing the data to delineate catchments and drainage networks

If only map data is available the procedure is to

- Work out the catchment boundary by analysing the contours
- Draw a grid on the map corresponding to the SHETRAN grid size
- Look at each grid square and if more than half of it is within the catchment boundary then a 1 is specified in the cathment grid
- Type in data in SHETRAN format

2.1.3 SHETRAN Line Numbers

The catchment grid for the catchment is specified in FR35. A maximum of 72 elements in the x direction is permitted. The SHETRAN grid sizes in the x direction are specified in FR9 and in the y direction in FR11.

2.2 Ground Surface Elevations

2.2.1 General

The ground surface elevation (meters above A.O.D) must be supplied to every grid square within the catchment boundary (see 2.1). Digital elevation models are usually available for the elevation in a catchment. For example, at the USGS website approximately 1km resolution data is available for the entire world. See http://edcwww.cr.usgs.gov/landdaac/gtopo30/gtopo30.html.

2.2.2 Processing Method

If a Digital Elevation Model (DEM) is available for a catchment this can easily be used with the catchment geometry in SHETRAN Windows

- If necessary increase the grid size of the DEM so it is the same as the SHETRAN grid size and the catchment geometry data
- Convert to ASCII format
- Use in SHETRAN Windows with the catchment geometry

Note, that flows in SHETRAN can only be in one of four directions (north,east,south and west), while flow in ARC/INFO can be in one of eight (N,NE,E,SE,S,SW,W,NW) and so there may be no sinks in ARC/INFO but some in SHETRAN

If only map data is available the procedure is to use the map prepared in 2.1.2 and then for elements within catchment boundary.

- For each grid square calculate the approximate mean elevation
- Analyse the elevations to see if there are any sinks (grid squares surrounded by higher land from which the water cannot drain). In particular consider the elevations around the catchment boundary. Increase the elevations of any sinks
- Type in data in SHETRAN format

2.2.3 SHETRAN line Numbers

The ground surface elevations for each element are specified in FR39.

2.3 River Network

2.3.1 General

The river or stream network in SHETRAN flows along the edge of the grid squares.

2.3.2 Processing Method

If a vector map of the river network is available the best method to convert this data into SHETRAN format is to

- Print a map of the DEM with the correct grid spacing for the SHETRAN simulation, overlain with the vector map of the river network
- By hand draw the SHETRAN river network along the edges of the SHETRAN grid squares
- Input the position of these river links into SHETRAN format by hand (difficult) .

If a Digital Elevation Model (DEM) of the catchment is available it is possible to use SHETRAN Windows to work out the flow accumulation in each grid square and hence the approximate position of the rivers. This is done automatically in SHETRAN Windows with the catchment geometry (or mask) and DEM data .

A threshold value for the accumulated flow is used to calculate the position of the rivers (for example a river is present if the flow accumulation is bigger than 20 grid squares).

See Tarboton et al. (1991) for details on this and other methods of extracting river networks from a DEM.

If only map data is available the procedure is to use the map prepared in 2.1.2 and then for rivers within the catchment boundary.

- By hand draw the SHETRAN river network along the edges of the SHETRAN grid squares
- Input the position of these river links into SHETRAN format by hand (difficult).

2.3.3 SHETRAN line Numbers

The river links are input separately for those that flow in a north-south direction and those that flow in an east-west direction. Those that flow in a north-south direction are input in FR35b and those in an east-west direction in FR35d.

2.4 River Network elevations

2.4.1 General

The bed elevations of the rivers or channels (meters above A.O.D) must be supplied to every river / channel link within the catchment boundary (see 3.1). The channels flow between two grid squares and the elevation of the channel bed plus the height of the channel cross-section is usually lower than the two adjacent grid squares. However, this is not required in SHETRAN and it is not always the case, for example for meandering rivers the channel banks are sometimes higher than the adjacent land. However, it is important that there is a downward flow path along all the river channels to the catchment outlet.

2.4.2 Processing Methods

At the moment this can either be done within Shetran Windows or by hand. If it is done within SHETRAN Windows then a parameter is used to define the drop between the adjacent grid squares and the channel bed elevation

2.4.3 SHETRAN Line numbers

The elevations of the channel beds are input in OC36. The values are input corresponding to the SHETRAN element number. The SHETRAN element numbers start counting river links first and then grid elements afterwards. River links are counted by considering the most southerly first and then if there are several of these the most westerly. The channel cross-sections are considered in 3.11.

2.5 Rainfall / Meteorological Station Distribution

2.5.1 General

Each element in a catchment uses data from a rainfall station and a meteorological station. The rainfall or meteorological station chosen for each element is the one with data that is most similar to the element. If little is known about the catchment this is the nearest rainfall or meteorological station, which the Thiessen polygon approach. However, the topography often has an important effect on the rainfall and by considering lines of equal rainfall (isohyets) and distance from a rainguage more accurate data can be obtained. More details can be found in Shaw (1994, Chapter 10).

Each meteorological station is generally considered to contain a rainguage and so the number of rainfall stations must be greater than or equal to the number of meteorological stations.

2.5.2 Processing Method

Data for the spatial distribution of rainfall and meteorological station is generally entered by hand

2.5.3 SHETRAN Line numbers

The number of rainfall and meteorological station is entered in FR29. If the same rainfall or meteorological station is used throughout the catchment this is entered in FR33. However, if there is a spatial distribution a 0 is entered in FR33 and the distribution is entered in FR44 for the meteorological station and FR47 for the rainfall stations. The data for the meteorological stations and rainfall stations can be entered in a variety of formats. See Section 4 for details.

2.6 Land Cover Distribution

2.6.1 General

Each element in the catchment is assigned a land cover, such as deciduous forest, arable land or grassland. Parameter values are then associated with each land cover type, details are given in 3.6 – 3.10.

2.6.2 Processing Method

If a digital distribution is available for a catchment this can easily be analysed to obtain the distribution. For example:

- If necessary increase the grid size of the digital distribution so it is the same as the SHETRAN grid size
- Specify the land-uses only if they are within the catchment boundary defined in 2.1.2 above
- Convert to ASCII format

If aerial photography, satellite imagery or map data is available the procedure is to

- Draw SHETRAN grid squares that are within the catchment on the map or picture
- Find the dominant land use in each grid square
- Type in the data in SHETRAN format

2.6.3 SHETRAN Line numbers

The number of different land-uses (or vegetation types) is specified in FR26. The spatial distribution is specified in FR50. Parameter values for each vegetation type are then specified from ET8 to ET18, see 3.6 – 4.10 for more details.

2.7 Soil Distributions and Depths

2.7.1 General

Each element in the catchment is a vertical column, which contains horizontal layers of soil and rock. For example, the element may contain a 1m deep loamy soil containing 2 different horizons above a 5m deep layer of sandstone rock. The distribution of the soils is considered here and the distribution of the geology in 2.8. Parameter values associated with each soil type are given in Appendix A. If using SHETRAN Windows only a single horizon (up to 10m deep) can currently be used.

2.7.2 Processing Method

If a digital distribution of soil types and depths is available for a catchment this can easily be analysed to obtain the distribution. For example:

- If necessary increase the grid size of the digital distribution so it is the same as the SHETRAN grid size
- Specify the soils only if they are within the catchment boundary defined in 2.1.2 above

- Convert to ASCII format

If soil map data is available the procedure is to

- Draw SHETRAN grid squares that are within the catchment on the map
- Find the dominant soil type and depth in each grid square
- Type in the data in SHETRAN format

However, the distribution of soils must be considered together with the geology distribution. See 2.8

2.7.3 SHETRAN Line numbers

The total number of soil and geology types is specified in VS03. The distribution of soil and geology for each element are considered together in VS08. Parameter values for each soil and geology type are specified in VS05, see 3.1 – 3.5 for details.

2.8 Geology

2.8.1 General

Each element in the catchment is a vertical column, which contains horizontal layers of soil and rock. For example, the element may contain a 1m deep loamy soil containing 2 different horizons above a 5m deep layer of sandstone rock. The distribution of the geology is considered here and the distribution of the soils in 2.7. Parameter values associated with each rock type are given in 3.1 - 3.5. This data cannot currently be used in SHETRAN Windows.

2.8.2 Processing Method

If a digital distribution of geology is available for a catchment this can be analysed to obtain the geology distribution. For example:

- If necessary increase the grid size of the digital distribution so it is the same as the SHETRAN grid size
- Specify the geology only if they are within the catchment boundary defined in 2.1.2
- Convert to ASCII format
- Convert to SHETRAN format using spreadsheet e.g. EXCEL

If hydrogeological map data is available the procedure is to

- Draw SHETRAN grid squares that are within the catchment on the map

- Find the dominant geology type and depth in each grid square

- Type in the data in SHETRAN format

However, the distribution of geology can be considerably more complex. It is may be important in a catchment to define the extent, thickness and connectivity of aquifers /aquitards. Data from borehole logs may give some information about the extent, thickness and connectivity of aquifers /aquitards. This information can only be processed by hand.

The geology distribution must also be considered together with the soil distribution. See 2.7

2.8.3 SHETRAN Line numbers

The total number of soil and geology types is specified in VS03. The distribution of soil and geology for each element are considered together in VS08. Parameter values for each soil and geology type are specified in VS05, see 3.1 – 3.5 for details.

Section 3 - Physical Properties

The preparation of data for the physical properties required in a SHETRAN simulation has been analysed in detail in DHI (1991), in which the SHE modelling system (previous version of SHETRAN) was transferred to the National Institute of Hydrology, India, and applied to a variety of catchments. The report focuses on obtaining soil data from field measurement. Some information is also given on vegetation parameters, and overland flow and channel parameters. Separate references to this report within each section are not made.

3.1 Porosity

The porosity of a soil or rock is the fraction (by volume) of water when the soil or rock is saturated. The values for soil range from 0.3 in sand soil to 0.6 in clay soil, and for rocks from 0 in a dense crystalline rock to up to 0.5 in a fractured karst limestone or basalt rock (Freeze and Cherry, 1979, pp37-39). The value of the porosity is usually measured by drying a sample of soil or rock in an oven at 105 °C. The porosity is the difference between the density of the grains within the soil or rock and the density of the dry soil or rock, divided by the density of the grains (Freeze and Cherry, 1979, p337). The porosity can also be estimated from the soil size distribution or the soil classification as in 3.2.2 below. Values of the porosity for a wide range of aquifers in England and Wales are given in BGS (1997).

The porosity of each soil is specified in VS05.

3.2 Soil Moisture Characteristic Function

3.2.1 General

The relationship between the soil-water potential (ψ) and the soil-water content (θ) is known as the soil moisture characteristic function or the soil water retention curve. The most important factor is textural and structural composition of the soil, although organic matter is sometimes important. Hysteresis effects may appear in the ψ–θ function and instead of a single curve there may be a family of curves, depending on the history of wetting and drying in the soil. This is not included in SHETRAN.

The ψ–θ relationship is also required for any rock specified in the catchment.

3.2.2 Data Sources and Processing Methods

<u>Pairs of ψ–θ values</u>

Pairs of ψ–θ values for soils can be obtained by measurements both in the laboratory and in the field, (Ragab and Cooper, 1990, pp6-18; Marshall and Holmes 1988, pp57-81). ψ–θ relationships have also been collated for a wide variety of different soil types (Case et al., 1983; Panian, T.F., 1987) and these curves could be adapted if information is known about the soils.

If more than 5 pairs of ψ–θ values are available for any soil in the catchment these can be used directly in SHETRAN. Intermediate values are obtained in SHETRAN by interpolation using a cublic spline method. The other method in SHETRAN is to fit curves to the pairs of values using the van Genuchten parameters α,n (van Genuchten, 1980). These parameters together with the saturated moisture content and the residual moisture content fully describe the ψ–θ relationship. A Fortran program is available to convert ψ–θ values into van Genuchten parameters. Panian (1987) contains fitted van Genuchten parameters for a wide variety of different soil types.

Data on $\psi-\theta$ values for rocks is sparse. Van Genuchten parameters have been fitted for a variety of sandstones in the United Kingdom (Digges La Toche, 1998). Van Genuchten parameters have also been used in SHETRAN simulations of coal aquifers (Adams and Younger, 1999) and a fractured slate at Slapton Wood, South Devon (Bathurst et al. 2004).

Soil Texture size distribution

The soil texture size distribution defines a soil according to the size of the particles within the soil. The British Standards Institution defines sand particles as being between 0.05 mm and 2.0 mm in size, silt between 0.002mm and 0.05mm, and clay less than 0.002 mm.

A large range of measured data exists between soil textures and soil water potentials. Saxton et al. (1986) fitted equations to this data, so that if the %clay and %sand of a soil is known the soil water potential can be estimated for a variety of soil moistures (a Fortran program is available). Thus pairs of $\psi-\theta$ values can be estimated. These pairs of values are statistical estimations and only take into account the textural influence and so are not as accurate as measured pairs of values, however, if no measurements are available they provide a very useful estimation. If the soils contain particles bigger in size than 2mm (gravel particles) or the clay content is greater than 60% these soils are outside the range of the equation and care must be taken using the results from the equation.

Having obtained pairs of $\psi-\theta$ values these can be used directly in SHETRAN or the van Genuchten parameters can be used.

Descriptive Soil Classification

Soils are labelled according to the proportion of the different fractions of clay, silt and sand they contain. The British classification can be seen in Appendix A. For example, a soil that contains 65% sand, 25% silt and 10% clay is a sandy loam soil.

Soils in the field can be easily classified by the feel and texture of the soil (Wiesner, 1970, pp32-37), or they can be classified by measuring the size distribution. The library of typical values for that soil classification can then be used (see appendix A). It is important to note that this is a simplification of the true soil moisture function on several accounts. Firstly the size distribution in the soil is only similar to the one specified in the library. Secondly the parameter values used for soils in the library only take into account the soil texture in the soil and other factors are important

3.2.3 SHETRAN Line Numbers

For each soil or rock type if van Genuchten parameters are being used this is specified in VS05 and the van Genuchten parameters are also specified there. If pairs of $\psi-\theta$ values are being used this is specified in VS05 and the pairs of values are given in VS05a. See 2.2.7 and 2.2.8 for the spatial distribution of the soil and rock types

3.2.4 Other References

Ma et al. (1999) considers the Brooks-Corey and van Genuchten functions and conversion between the functions. Chen and Wheater (1999) consider variability and uncertainty in the use of the soil moisture characteristic function.

3.3 Saturated Conductivity

The saturated conductivity (K_{sat}) is the rate of discharge per unit area through a saturated medium. It varies considerably in soils from less than 0.01 m/day in clay soils to over 100 m/day in gravel alluvium. In rocks there is an even larger range from less than 10^{-6} m/day in unfractured igneous rocks to over 10 m/day in karst limestone (Freeze and Cherry, 1979, pp26-30). For details on measuring the saturated conductivity see Marshall and Holmes (1988, pp95-97) and Ragab and Cooper, (1990, pp18-31). If no measurements are available it can be estimated from measurements of the particle size distribution (Ragab and Cooper, 1990, pp52-55; Vukovic and Soro, 1992). It can also be estimated from the soil classification, (Rawls et al. 1982), Appendix A. Values of the hydraulic conductivity for a wide range of aquifers in England and Wales are given in BGS (1997).

The saturated conductivity is defined for each soil and rock in the x,y and z directions in VS05.

3.4 Conductivity function (K,θ) relationships

3.4.1 General

The hydraulic conductivity (K) in a soil is greatest when the soil is saturated ($\theta = \theta_{sat}$), the whole pore space is involved with the flow of water through the soil. As the soil dries out the larger pores spaces no longer hold any water, the conductivity is confined to the smaller pore spaces and the hydraulic conductivity decreases. The conductivity also decreases because the path of flow becomes more tortuous. As with the soil moisture characteristic function, the most important factor in the conductivity function is the textural and structural composition of the soil.

The conductivity function is also required for any rock specified in the catchment. However, there is sparse data on K–θ values for rocks

3.4.2 Data Sources and Processing Methods

Pairs of K–θ values

Details on measuring K–θ values in the field, the laboratory and predictive methods are given in Ragab and Cooper (1990, pp33-44 and pp55-58). K–θ relationships have also been collated for a wide variety of different soil types (Case et al., 1983) and these curves could be adapted if information is known about the soils.

If more than 5 pairs of K–θ values are available for any soil in the catchment these can be used directly in SHETRAN (if pairs of ψ–θ values are being used). Intermediate values are obtained in SHETRAN by interpolation using a cubic spline method.

It is also possible to fit an Averjanov function to the pairs of K–θ values. In this equation the relative conductivity (K/K_{sat}) depends on the effective saturation of the soil to the power n, where n depends on the soil type (Maulem, 1978). Values of n range from 1.0 up to more than 20 with normal values in the range from 2.5 – 4.0. Again this requires that pairs of ψ–θ values are being used.

If van Genuchten parameters are being used for ψ–θ values then neither the pairs of K–θ values nor the Averjanov function can be used for K–θ values. Instead K–θ values are automatically defined once the saturated conductivity has been specified.

It has been found for a wide variety of rock types in SHETRAN simulations that van Genuchten parameters do not adequately simulate the K–θ values. For simulations involving rocks, an Averjanov function or pairs of K–θ values allow the most flexibility. For example in chalk rocks in the Kennet catchment the van

Genuchten parameters produced poor results and the best results were obtained using an Averjanov function with the value of n equal to approximately 20.

Soil Texture size distribution

If the soil texture distribution is known, then this data can be used to estimate the n parameter in the Averjanov function (Maulem, 1978, Table 2). This method should be used if pairs of ψ–θ values are being used.

If van Genuchten parameters are being used for ψ–θ values then K–θ values are automatically defined once the saturated conductivity has been specified.

Descriptive Soil Classification

If the soil texture classification is known, then this data can be used to estimate the n parameter in the Averjanov function (Maulem, 1978, Table 2). This method should be used if pairs of ψ–θ values are being used.

If van Genuchten parameters are being used for ψ–θ values then K–θ values are automatically defined once the saturated conductivity has been specified.

3.4.3 SHETRAN Line Numbers

For each soil or rock type if van Genuchten parameters are being used this is specified in VS05 and the van Genuchten parameters are also specified there. If pairs of K–θ values are being used this is specified in VS05 and the pairs of values are given in VS05a. If an Averjanov function is being used this is specified in VS05 together with the exponent n used in the Averjanov function. See 2.2.7 and 2.2.8 for the spatial distribution of the soil and rock types.

3.5 Specific Storativity

The specific storativity is important in confined aquifers. It is defined as the volume of water released from an area of confined aquifer per unit decline in head. In the confined aquifers the pores are not drained but water is released from 'elastic storage' by expansion of the water and the compaction of the aquifer. Younger, (1993) found the most important factor affecting the value of the specific storativity is the aquifer compressibility. Using typical values of aquifer compressibility and assuming a porosity of 15% he estimated specific storativity values. These ranged from $9.8 * 10^{-3}$ (m^{-1}) in clay aquifers, to $1.05 * 10^{-5}$ in a coarse sand, medium gravel or highly fissured rock aquifer, to $7.46 * 10^{-7}$ in an unfissured rock.

The specific storativity (m^{-1}) of each soil is specified in VS05.

3.6 Vegetation cover indices

3.6.1 General

The vegetation cover indices define how the vegetation covers the land surface. Two factors are important in SHETRAN. Firstly, the division between the proportion of ground that is always bare and ground which is covered by vegetation (equal to the maximum amount when the vegetation is in leaf), known as the plant area index (PLAI). Secondly, the ratio of the total leaf area to the area of ground covered by vegetation, known as the canopy leaf area index (CLAI). For a variety of vegetation types, e.g., deciduous forest or arable land, the canopy leaf area index varies with the time of year; this can be included in the model.

The vegetation cover indices are used in a Rutter et al. (1972) type model to split the precipitation between that which falls directly on the land surface and that which is intercepted by the canopy. SHETRAN is not very sensitive to variations in these values.

3.6.2 Measured

Measurement of the plant area index can be made by going into the catchment and analysing each vegetation type. The value can range from 0 when there is no vegetation to 1 when the vegetation completely covers the land surface. Similarly the canopy leaf area index can be measured, although this often varies seasonally. Varying from around 0.1 for forests in the winter to up to 6 in the summer (values greater than 1 imply the canopy contains leaves that lie under other leaves). However, if the value is greater than one then the value of one is used in the analysis in SHETRAN. Measured values for seasonal variations in the leaf area index for a variety of crops are available in Burman and Pochop (1994,pp155-157).

3.6.3 Standard Vegetation types

Values of the vegetation cover indices for standard vegetation types are given in Appendix B. Values for the plant area index range from 0.3 in urban areas to 0.9 in forests. Values of the canopy leaf area index at its maximum seasonal extent range from 1 to 4. However, in some vegetations, particularly arable and deciduous land, the value can be considerably smaller at certain times of the year and time varying values should be incorporated into SHETRAN.

3.6.4 SHETRAN Line Numbers

In SHETRAN a value is input for each vegetation type in ET8. Time varying plant area indices and canopy leaf area indices can also be included in the model in lines ET10, ET12 and ET14.

3.7 Canopy Storage

3.7.1 General

The canopy storage capacity is the maximum quantity of water that can be held on the aerial portions of vegetation. It is usually expressed as an average depth for the vegetation in terms of liquid water equivalent (often in mm). Once the capacity has been exceeded further intercepted water either drips from the canopy or runs down the stems. The value of the canopy storage capacity depends on a variety of factors such as surface area of the leaves, their roughness, orientation, arrangement and the forces of wind and gravity that dislodge them. The value is used in a Rutter et al. (1972) type model together with the vegetation cover indices (3.6) and the drainage parameters (3.8) to calculate the amount of water on the canopy at any one time and from this information evaporation from intercepted rainfall is calculated. SHETRAN is not very sensitive to variations in the canopy storage capacity.

The canopy storage capacity is generally higher in forest than in other vegetation and this together with the lower aerodynamic resistance factor in forests (see 3.10.2) are the reasons that high evaporation of intercepted water found in forests. Zinke (1967) found that interception losses in coniferous forests commonly range from 15 to 40% of the annual precipitation whilst in deciduous forests from 10 to 25% (see also Appendix C).

3.7.2 Measured

The traditional method of measuring canopy storage uses an indirect method. Rainfall is measured inside and outside the vegetation and some assumptions are made on the process of interception in order to calculate the canopy storage. Klaassen et al. (1998) consider the use of directly measuring canopy storage using microwave transmission and compare the results obtained with a variety of other methods such as tree weighing and gamma ray attenuation.

3.7.3 Literature values

Zinke (1967) compiled literature data on canopy storage capacities for forests. Values for deciduous forest range from 0.1 – 2.0 mm and for coniferous forest from 0.3 to 8.0mm. Similar values can be found for forests in Klassen et al. (1998). Leyton et al. (1967) compiled literature data for a variety of vegetations. Values for range from 0.007 to 0.026 for grassland and 0.036 to 0.090 for bracken. Rutter (1975) has compiled data for a variety of vegetation types, with values in the same range. Values of the canopy storage capacity for seven standard vegetation types are given in Appendix B.

3.7.4 SHETRAN Line Numbers

In SHETRAN a value is input for each vegetation type in ET8. Time varying canopy storage can also be included in the model in lines ET10, ET12 and ET14.

3.8 Drainage Parameters

3.8.1 General

The drainage parameters define how water that is held in the canopy drain from it to the ground surface. There are two parameters that define this drainage using an equation developed by Rutter et al. (1972). The Rutter k (or drainage rate parameter) gives the rate of drainage when the canopy is at its storage capacity. The Rutter b parameter is used in an exponential function and describes how the drainage rate falls as the canopy dries. SHETRAN simulations are not very sensitive to changes in the Rutter parameters.

3.8.2 Literature values

Literature values for the two Rutter drainage parameters are given in Rutter et al. (1972,1975), Calder (1990, p11) and Dunn and Mackay (1995). Values for the Rutter k parameter range from $3.3 * 10^{-5}$ to $4.6 * 10^{-6}$ mm/s. Values for the Rutter b parameter range from 1.76 to 5.1 mm^{-1}.

3.8.3 Standard Vegetation types

Values of the Rutter drainage parameters for standard vegetation types are given in Appendix B. Values for the Rutter k parameter (CK in SHETRAN) range from $1.4*10^{-5}$ to $1.9*10^{-5}$ mm/s. Values for the Rutter b parameter (Cb in SHETRAN) range from 3.7 to 5.1 mm^{-1}.

3.8.4 SHETRAN Line Numbers

In SHETRAN a values for both Rutter drainage parameters are input for each vegetation type in ET8.

3.9 Root Density Functions

3.9.1 General

The root density function defines the total rooting depth and the proportion of roots in each layer (or cell). Thus the total sum of the root densities should be equal to one. This function is used to estimate the water removal by transpiration from each depth. In those depths with a higher root density function there is a greater transpiration rate. SHETRAN simulations are not very sensitive to changes in the root density function, an approximate function is generally satisfactory.

3.9.2 Measurements and Literature Values

Measurements of root density functions can be made by digging soil pits for different vegetation types in different parts of the catchment and analysing the rooting depth and the proportion of roots at a variety of depths.

Literature values can also be used to estimate the rooting depth and densities. Gregory (1988, pp119-141) summarizes experiments that have measured maximum rooting depth and the root density function for a variety of crops. Burman and Pochup (1994, pp115-117) also give details on several experiments that have calculated the root density function. They also details on estimating the root density function using a simple rule of thumb, in which the root density is divided into quarters from the surface, and the first quarter has 40% of the roots, the 2nd 30%, the 3rd 20% and the final quarter 10%. Dunn and Mackay (1995) estimated the rooting depth for eight different vegetation types used in a SHETRAN simulation and these reached a maximum of 3m in forest. They had an exponential decreasing distribution from the ground surface to this estimated maximum rooting depth. However, care should be taken using literature values because the root are highly dependent on both the physical and nutrient conditions in the soil (Gregory 1988, pp119-141).

3.9.3 Standard Vegetation types

Values of the root density function for standard vegetation types are given in Appendix B2. Care must be taken that the maximum rooting depth is less than or equal to the maximum depth of the soil column.

3.9.4 SHETRAN Line Numbers

In SHETRAN the root density function in input not according to the depth below ground but the proportion of roots in each cell starting at the ground surface. The number of cells that contain roots are input for each vegetation type in ET8. For each of these cells there is a line in ET18 (starting at the ground surface) containing the depth to the cell from the ground surface (which is input but not used in SHETRAN) and the proportion of roots in that cell.

3.10 Evapotranspiration Parameters

3.10.1 General

Evapotranspiration is based on the model developed by Rutter et al. (1972), an application of this model to a forest canopy was performed by Gash and Morton (1978). The amount of rainfall intercepted by the canopy, the amount which drains from the canopy and that which arrives on the bare ground are calculated using the parameters from the vegetation cover indices (3.6), canopy storage capacity (3.7) and drainage parameters (3.8). Evaporation can then occur from intercepted storage and bare soil, and transpiration can take place. This evapotranspiration can then be calculated in one of two ways. Firstly, using the Penman-Monteith equation (Monteith, 1965) which uses full meteorological data (4.1) and allows for the use aerodynamic and canopy (or surface) resistances which are considered in 3.10.2 and 3.10.3. Secondly using pre-supplied potential evaporation, e.g. Penman reference crop evaporation, (4.2) and modifying this to take into account the soil moisture conditions.

Both methods produce satisfactory calculations of the actual evapotranspirsation rate. The main problem is that using the pre-supplied evaporation rates the intercepted evaporation from tall vegetation is underestimated. See Appendix C for details.

The following definitions are taken from Shuttleworth (1993) and are used in 3.10

E_p – Potential evaporation of water evaporated from an idealized, extensive free water surface under existing atmospheric conditions.

E_{rc} – Reference Crop evaporation from an idealized grass crop with a fixed crop height of 0.12m, an albedo of 0.23 and a surface resistance of 69 s/m. (equivalent to a crop of short grass, not short of water).

3.10.2 Aerodynamic and canopy resistance – measurements and literature values

If evapotranspiration is calculated using the Penman-Monteith equation then aerodynamic and canopy resistances can be used. In fact, Bevan (1979) found that the Penman-Monteith equation was very sensitive to these values. Similarly overall SHETRAN simulations are sensitive to these values.

The aerodynamic resistance r_a depends on the friction of air flowing over the vegetation surface. There are various methods used to calculate the value (Burman and Pochop, 1994, pp87-90) but all have a significant empirical component. One method that can be used directly in SHETRAN is to calculate the value directly from the wind velocity profile using the logarithmic boundary layer equation (See Appendix C2 for details). As well as the windspeed, values for the zero-plane displacement and the roughness height for the particular vegetation are necessary and these are also given in Appendix C2.

The canopy resistance r_c referred to here is the bulk stomatal resistance of the whole plant canopy. It also takes into account the dryness of the soil. Equations for calculating the value for wet soils depending on the leaf area index have been developed (Burman and Pochop, 1994, pp89-90). Thompson et al. (1981) calculate evapotranspiration using the Penamn-Monteith equation in the MORECS model. They recommend values for a variety of different vegetations ranging from 40 s/m for cereals to 120 s/m for upland vegetation. These values and values from Szeicz and Long (1969) are summarized in Burman and Pochop (1994, pp 147-148).

Burman and Pochop (1994, pp 147-148) also summarize data on how canopy resistances respond to changes in soil water status. There is often a dramatic increase in the resistance. For example, Szeicz and Long (1969) found that for a grass-clover crop in Denmark it increased from 26 s/m to 400 s/m, and Russell (1980) found that for a barley plot it increased from 30 s/m to 180 s/m.

3.10.3 Aerodynamic and canopy resistance –SHETRAN Simulations

Dunn and Mackay (1995) used aerodynamic and canopy resistance for eight vegetation types in the Tyne valley, northern England. Aerodynamic resistances were calculated using the logarithmic boundary layer equation, with average wind speeds used and fixed values obtained. Values ranged from 6 s/m for evergreen forests to 150 s/m for urban areas. Literature values were used for canopy resistances although checks were carried out that the evapotranspiration rates were in agreement with field measurements. Values in wet soils ranged from 90 s/m in arable land to 500 s/m in felled areas. These values were increased as the soils dried out.

3.10.4 Actual / potential Evapotranspiration ratio -Literature values

If full meteorological data is not available the reference crop evaporation (E_{rc}) can be calculated using Penman equation or more simple methods can be used (see Section 4 for details). Generally, these give the value of E_{rc} for short grass freely supplied with water (although care should be taken about exactly what has been measured). In SHETRAN simulations intercepted evaporation occurs at this rate (although for taller vegetation, such as forests, this potential rate E_{rc} is insufficient, see Appendix C for details). Transpiration and evaporation from bare soil can occur at this rate but are modified using a actual/potential evapotranspiration ratio function (input into SHETRAN) that can take into account a crop coefficient and a soil water coefficient.

$$E_a = K_c * K_s(\theta) * E_{rc}$$

Where:

K_c = crop coefficeient

$K_s(\theta)$= Soil water coefficeient

$K_c * K_s(\theta)$= actual/potential evapotranspiration ratio (E_a/E_{rc}) which is input into SHETRAN

The crop coefficient depends on many factors especially on the stage in its growth, Wallace (1995) gives details on other factors that affect it. Shuttleworth (1993, pp4.41-4.44) give the crop coefficient for a wide variety of agricultural crops at different stages in their growth and in different climates. These typically range from 0.3 at the start of the growing season to 1.2 in the mid-season. Grassland crops have a smaller annual change ranging from around 0.9 to 1.05. For forest the crop coefficient is generally around 0.8, which is less than for grassland therefore producing less transpiration. However, a higher value for forests is generally used in SHETRAN see Appendix B3 for details.

A variety of different relationships have been suggested for $K_s(\theta)$ (Rutter 1975; Calder 1983) although it depends on variety of factors such as the plant, the climate and the soil. Feddes et al (1976) found that a function in which the $K_s(\theta)$ reduced linearly as the soil moisture dropped from field capacity to wilting point worked well.

There have been a number of experiments attempting to find the $K_s(\theta)$ function. For example, van Bavel (1967) considered an alfalfa crop in Arizona, USA, Szeicz and Long (1969) a grass-clover crop in Denmark, Palmer et al. (1964) saltbush and upland cotton in Australia and Russell (1980) a barley crop in the UK. They generally found that $K_s(\theta)$ was equal to 1 from saturation to about 50 – 80% of the field capacity, it then reduced to 0 at wilting point.

3.10.5 Actual / potential Evapotranspiration ratio – Standard vegetation types

Actual/potential evapotranspiration ratios depend on both the crop coefficient and the soil water coefficient, see 3.10.4 for details. Using the measurements and literature values considered in 3.10.4 and the values from previous SHETRAN simulations (Parkin et al, 1996; Lukey et al 1995) E_a/E_{rc} ratois have been developed for a number of standard vegetation types, see Appendix B3 for details. These values have been found to require modifications in different climates and the overall simulation is sensitive to the values used.

3.10.6 SHETRAN Line Numbers

If aerodynamic and canopy resistances are being used this is specified in MODE in ET8. The aerodyanmic resistance (or the anaemometer height, zero plane displacement and vegetation roughness height) are also specified in ET8. The canopy resistance is specified in ET8 if it does not depend on the wetness of the soil. If the canopy resistance does depend on the wetness of the soil this is specified in ET16. If the actual / potential evapotranspiration ratio is being used this is specified in MODE in ET8. The actual / potential evapotranspiration function is specified in ET16. The above information is repeated for each vegetation type.

3.11 Channel Cross-Sections

The channel cross-sections are required for every link element in SHETRAN. The cross-section is defined as pairs of widths and depths of the channel above the channel-bed. The first pair defines the width of the bottom of the channel with a depth of zero, the final pair the width and depth of the channel when it is full of water. Further pairs of values can be specified between these two pairs if it is necessary to define the channel shape. Thus any symmetrical cross-section using straight lines can be defined.

Measurements of channel cross-sections can be easily made. However, although the size of the channel is important an approximate cross-section provides sufficient accuracy for SHETRAN simulations.

Cross-sections can be defined into categories of similar shapes in OC31, OC33 and OC34, with the category type for each link specified in OC36. Individual cross-sections can be defined in OC31, OC36 and OC37.

3.12 Roughness Parameters in River Channels

3.12.1 General

Water in the river channels is routed along the channels using the diffusive wave approximation of the St. Venant equations. This equation requires a roughness coefficient which in SHETRAN is the Strickler coefficient or the inverse of Manning roughness coefficient, n. The higher the value of the Strickler coefficient the smaller the roughness and the faster the flow.

3.12.2 Literature Values

Values for the Manning's roughness / Strickler coefficient are fairly well defined for flow in open channels. For example, Chow (1973, pp116-123) has pictures of various open channels and the corresponding Manning roughness coefficient

3.12.3 SHETRAN Line Numbers

Strickler parameters for the roughness are specified for each channel link in OC36.

3.13 Roughness Parameters on Land

3.13.1 General

Surface water outside the channel system can arise through infiltration excess (when the rainfall rate exceeds the infiltration rate) or by saturation excess (when the groundwater table rises to the surface). This surface water is then routed overland in both the x and y directions using the diffusive wave approximation of the St. Venant equations. These equations require one parameter, the friction factor, which is an effective roughnesss coefficient that Engman (1986) specified as including the effects of "raindrop impact, channelization of flow, obstacles such as litter, crop ridges, rocks, and roughness from tillage, the fractional drag over the surface, and erosion and transport of sediment". This effective roughness coefficient in SHETRAN is the Strickler coefficient or the inverse of Manning roughness coefficient, n. The higher the value of the Strickler coefficient the smaller the roughness and the faster the flow.

3.13.2 Literature Values

Values for the Manning's roughness coefficient for overland flow are given for a variety of soil surface conditions in Engman (1986), more values for tilled soils are specified in Mohamoud (1992). Strickler parameters can be easily found by taking the inverse of these values. These range from 2 for deep grassland up to 100 for concrete.

However, these values are taken from small erosion plots and users of these values should be aware of their potential limitations. In particular very high or low intensities of rainfall, channalization of the overland flow, long slopes that simulate large surface water depths.

3.13.3 SHETRAN Line Numbers

Strickler parameters for the roughness can be specified as being the same throughout the catchment using OC1a and OC3a. They can be specified in categories of similar vegetation/soil types using OC1a and OC16 for the x direction categories and OC19 for the y direction categories. They can also be specified for each individual grid square using OC1a, OC3a, OC16 for the x direction and OC19 for the y direction.

Section 4 - Meteorological Data

4.1 Full meteorological data

4.1.1 General

Full meteorological data contains data at regular time intervals, normally hourly. The following data is required for each time: rainfall during time period (mm), net radiation (W/m^2), windspeed (m/s), air temperature (°C), slope of saturation vapour pressure/temperature curve (mb/°C), vapour pressure deficit of air (mb). The measured potential evapotranspiration (mm/hr) can also be input although it is not essential

4.1.2 Meteorological data file (MED)

If full meteorological data at regular time intervals is available for the whole of the simulation a meteorological data file (MED) can be used. The data in the MED file must be in the correct format and a program (met2fullshe.f) is available to convert data from a Cambell logger weather station to MED file format.

If a MED file is being used then actual evapotranspiration can be calculated using the Penman-Monteith equation. It is also possible to calculate the actual evapotranspiration using the actual/potential evapotranspiration ratio (see 3.10 for details). However, if data is missing it is difficult to infill a MED file. The file is also considerably larger than the rainfall (PRD) and potential evaporation (EPD) files.

4.1.3 Rainfall file (PRD) and potential evaporation file (EPD)

If full meteorological data is available it can be converted into rainfall data in a PRD file and breakpoint potential evaporation in an EPD file.. A program (met2she.f) is available to convert data from a Cambell logger weather station to a PRD and EPD file.

If PRD and EPD files are being used actual evapotranspiration can only be calculated using the actual/potential evapotranspiration ratio (there is insufficient information to use the Penman-Monteith equation, see 3.10 for details). However, it is easy to infill missing rainfall or potential evaporation data and the PRD and EPD files are considerably smaller than the MED file

4.1.4 SHETRAN Line Numbers

To use a MED file certain information must be specified in the evapotranspiration data file (ETD). In ET2 that a MED file is being used. In ET4 the time step in the MED file. In ET6 whether potential evapotranspiration is included in the MED file. To use a PRD and EPD file certain information must be specified in the evapotranspiration data file (ETD). In ET2 that PRD and EPD files are being used, in ET4 the timestep. SHETRAN line numbers for the evapotranspiration parameters are specified in 3.10.

4.2 Hourly rainfall and potential evapotranspiration data

Rainfall (PRD file) and potential evaporation (EPD file) are both read in at regularly spaced intervals. Actual evapotranspiration can only be calculated using the actual/potential evapotranspiration ratio (there is insufficient information to use the Penman-Monteith equation)

To use a PRD and EPD file certain information must be specified in the evapotranspiration data file (ETD). In ET2 that PRD and EPD files are being used, in ET4 the timestep for data in the PRD and EPD file.. SHETRAN line numbers for the evapotranspiration parameters are specified in 3.10.

4.3 Daily rainfall and potential evapotranspiration data

Daily rainfall is of insufficient resolution to satisfactorily drive SHETRAN. It is necessary to disagregate the daily rainfall to hourly data. Two main methods are available. Firstly to use the RAINSIM program developed at the University of Newcastle. This is based on the generalized Newman-Scott rainfall model and which uses statistical information from the daily rainfall to generate rainfall events and hence hourly rainfall. Secondly, if hourly data is available from nearby weather stations the timing of the rainfall events can be obtained using this data and the rainfall volumes from the daily data. Daily evapotranspiration data is of sufficient resolution to drive SHETRAN satisfactorily.

Having obtained hourly rainfall data and using the daily potential evaporation data use rainfall and potential evaporation files (EPD and PRD) as in 4.2.

4.4 Hourly/Daily rainfall and air temperature data

Daily potential evpaoration data can be calculated from the mean daily air temperature using the Blaney-Criddle formula. This equation is an empirical formula, which as well as air temperature requires the daily percentage of total annual daytime hours, which can be found in tables). Various versions of the equation have been developed over the years and details of some these can be found in Burman and Pochop (1994, pp 94-97 and pp143-146). These include incorporating monthly crop coefficient and sunshine and wind data. A Fortran program is available to calculate daily potential evaporation using the Blaney-Criddle formula, it can also be calibrated using monthly coefficients if any nearby measured potential evaporation is known.

Having obtained potential evaporation data the procedure is as in 4.2 and 4.3.

Section 5 - Individual Parameters

5.1 Basic Timestep

The basic timestep is is usually 1 hour or 2 hours. However, the timestep length is automatically reduced during rainfall. The basic timestep is set in FR21.

5.2 Maximum River Discharge

The maximum river discharge (m^3/s) is set to be slightly larger than the maximum possible flow. It is used to stop the simulation if there are problems with the numerical solution within SHETRAN producing spurious results. An approximate value is the catchment area (km^2)*max rainfall rate (mm/hr)*0.28. The value is set in FR21.

5.3 Weir locations, sill elevations, and coefficients

Weir locations, sill elevations and downstream water elevation (if it is at the catchment edge) and coefficients should all be known from the weir design details. The submergence ratio for weir is usually set to 0.7. The weir coefficient depends on the catchment size: with a value of approximately 6 for a catchment of 1km^2, 10 for a catchment of 50 km^2 and 50 for a catchment of 100 km^2. These values are set in OC38.

Section 6 - Calibration / Validation Data

6.1 River and Spring Discharges for Calibration or Validation

6.1.1 General

The standard method of assessing a catchment model is to perform a split-sample simulation. In this the data for the catchment is divided into two sets. In the first set calibration is performed by modifying the parameters to get the best fit available between the simulated and measured discharge data. Using the second set the model is validated by performing the simulation and comparing the measured and simulated discharges. A different method of validation is now also used in SHETRAN, this is 'blind validation' (Ewen and Parkin, 1996) in which parameters are given appropriate values or ranges of values and the discharge data is compared to the simulated data without any calibration. In both cases river or spring discharge data is necessary.

6.1.2 Stage/Discharge Relationships

To obtain the discharge data the standard procedure is to obtain a stage/discharge relationship. Single points in the stage/discharge relationship are obtained by measuring the depth of the water (stage) at a point in the river and then calculating the flow. If this is performed for a wide variety of flows a complete stage/discharge relationship can be obtained. Having obtained a stage/discharge relationship the discharge is known for any water level (stage) measurements. The flows are usually calculated using the velocity-area method, in which the velocity is measured using current meters (Shaw, 1994, pp106-112). A computer program is available which calculates a theoretical stage/discharge relationship for flumes and weirs using the dimensions of the flume or weir.

6.1.3 Comparing the Measured and Simulated discharge

Flow data can be obtained from any river link or grid element in SHETRAN. The data that is required is specified in a PPD file at the start of the simulation. Using SHEGRAPH (a program to produce text files and graphical displays of SHETRAN output) this data can be output as a time series and compared to the measured discharge using standard software. Comparisons of measured and simulated discharge data from a SHETRAN simulation using the 'blind validation' technique can be seen in Parkin et al. (1996).

6.2 Water Table and Piezometric Levels

Water table levels have been used both to calibrate and validate SHETRAN simulations. In Birkinshaw and Ewen (2000) the simulated discharge at the outlet of the Slapton Wood catchment, Devon, UK, is calibrated against the measured discharge. A validation of the water flow simulation is then performed by comparing the simulated and measured water table levels from eighteen dipwell measurements throughout the catchment (validation of the nitrate component of SHETRAN is also performed). In Parkin et al. (1999) a SHETRAN simulation of a hillslope in West Cumbria is performed. With no discharge measurements, calibration of the water flow component is carried out by comparing the simulated and measured water table levels (validation of the solute component of SHETRAN is then performed).

6.3 Soil Moisture or Tension Data

Using a previous version of SHETRAN a 'blind validation' was performed on the Slapton Wood catchment, Devon, UK (Bathurst et al., 2004). As well as comparing the simulated and measured discharge and the simulated and measured water table levels, the simulated soil moisture and tension levels were compared against the measured ones. As in Parkin et al. (1996) a range of parameter values were used in the simulations and this produced a range in the simulated soil moistures and tensions and this was used in the comparison with the measured values.

Section 7 - Initial Conditions

7.1 Depth of Water – Grid Squares

The depth of surface water in the grid squares is nearly always set to zero. If they are set to zero, appropriate values will be obtained rapidly during the initial stages of the simulation.

If the initial depth of water on all the grid squares is zero this is entered in OC1a. If there is an initial depth of water on some grid squares this is specified in OC1a and the depth on all the grid squares is entered in OC6 and OC7.

7.2 Depth of Water – Channels

The depth of surface water in the channels is nearly always set to zero. Appropriate values will be obtained rapidly during the initial stages of the simulation.

The initial depth of water is specified for each river link in OC36.

7.3 Initial Subsurface Conditions

7.3.1 General

The importance of initial subsurface systems depends entirely on the catchment. For surface water systems the effect of the initial conditions die away after a few days. For deep soil and groundwater systems the initial conditions are more important since the influence will be felt over a period of years

7.3.2 Equilibrium Profile

This is used if no other data is available or in situations when the effect of the initial conditions die away rapidly. Using this method generally a 'run-in' period is included at the start of the simulation, to allow the spurious effects of initial conditions to die away. Alternatively the whole simulation can be performed and subsurface conditions at a time of year appropriate to the start of the simulation can be extracted and used as initial conditions (see 7.3.3 and 7.3.4).

7.3.3 Phreatic Surface Elevations

If phreatic surface elevations are known for every element these can be used as the initial conditions for the simulation. Alternatively, a preliminary simulation can be performed using equilibrium conditions and the phreatic surface elevations extracted at a time of the year appropriate to the start of the simulation.

7.3.4 Potentials

Potentials are useful as an initial subsurface condition in simulations with a complex subsurface geometry or complex boundary conditions. They are generally extracted from premlininary simulations that have been performed with an equilibrium profile or phreatic surface elevations as the initial subsurface conditions. The data is extracted from the end of these simulations.

7.3.5 SHETRAN Line Numbers

Equilibrium initial subsurface conditions are specified in VS03 and VS04. The initial depth of the phreatic surface is often set to ½ the minimum soil column depth for elements in the catchment if no other information is known. The use of phreatic surface depths as the initial subsurface condition is specified in VS03. The values of the phreatic surface elevations for each grid element are input in a VSI file. The use of potentials as the initial subsurface condition is specified in VS03. The values of the potentials for each cell in each grid element, starting at the bottom, are input in a VSI file.

Section 8 - Boundary Data (optional)

8.1 Well data

Wells can be incorporated in SHETRAN to extract water from the subsurface. The water extracted from the well can be applied to another part of the catchment if there is irrigation taking place.

Details of the number of wells is specified in VS11 in the VSD file. For each well the SHETRAN element number of the position of the well and the element number the extracted water is applied to (0 if it is taken from the catchment) is specified in VS12a. The depth below ground of the top and the bottom of the well screen is specified in VS12b. The time varying extraction rate of water from the well is given in a WLD file using breakpoint format (see Section 10 for details of breakpoint format).

Parkin et al. (1999) used a well in their simulation of a hillslope. A negative extraction rate was used in the WLD to account for water containing a solute being pumped into the catchment.

8.2 Spring data

Springs can be incorporated into SHETRAN to move water from the subsurface to the surface. Details of the number of springs is specified in VS11. For each spring the SHETRAN element number of the position of the spring and the element number the spring water is applied to (0 if it is not within the catchment) is specified in VS13a. In VS13b the depth of the spring source, the elevation of the discharge point and the spring coefficient are specified.

8.3 Overland flow data in/out of the catchment

8.3.1 Flow Data

SHETRAN simulations are often performed for a complete hydrological catchment. However in some cases only part of a catchment is considered, for example, in the NELUP hydrological simulation of the Tyne valley (Adams et al. 1995), the catchment is split into 15 subcatchments. SHETRAN simulations of the lower subcatchments require details of the upper subcatchments river discharges. This information can be supplied using overland flow boundary data. Overland flow data can also be supplied to simulate the application of irrigation water, where the water has been obtained from outside the catchment. It can also be used to force SHETRAN to produce set flows out from rivers or set overland flows.

The number of flow or flux boundary condition categories are specified in OC21. The SHETRAN element numbers in each category type are specified in OC25 and the time-varying flows (m^3/s) for each category is given in a OFB file using breakpoint format (see Section 10 for details of breakpoint format).

8.3.2 Head Data

Surface head data is used to specify the surface water head (meters above ground) at any element in the catchment. Thus if the water head is specified to be 1 meter above ground, there will be a surface water depth of 1 meter in this element. The surface head can also be time-varying.

The number of head boundary condition categories are specified in OC21. The SHETRAN element numbers in each category type are specified in OC23 and the time-varying head (m) for each category is given in a OHB file using breakpoint format (see Section 10 for details of breakpoint format).

8.3.3 Polynomial Data

Polynomial data is used to specify the overland flow in an element depending on the surface water depth and five coefficients using the equation:

$Q = AH^4 + BH^3 + CH^2 + DH + E$

Where A-E are coefficients, H is the surface water depth (m) and Q is the flow (m^3/s). This was used in the SHETRAN simulation of a hillslope plot in West Cumbria, UK to specify the surface flows out from the bottom of the plot (Parkin et al., 1999).

The number of polynomial function categories are specified in OC21. The SHETRAN element numbers in each category type are specified in OC27 and the five coefficients for each category type are given in OC29.

8.4 Lateral subsurface flow data in/out of the catchment

8.4.1 Flow Data

Lateral subsurface flow data (m^3/s) is used to specify the flow to or from any soil or aquifer layer for any element in the catchment.

The number of categories for lateral flow boundary conditions is specified in VS11. The elements which have a lateral flow boundary condition are given the number 3 in VS14 and the category type for each element is specified in VS15. For each category type the number of soil or aquifer layers with lateral flow boundary condition are specifed in VS16a and the layer numbers specified in VS16b. In an LFB file the time-varying flow data is input for each layer in each category type. The time-varying data is input in breakpoint format (see Section 10 for details of breakpoint format).

8.4.2 Head Data

Lateral subsurface head data (m) is used to specify the head at any layer for any element in the catchment. Thus in the SHETRAN simulation of a hillslope plot in West Cumbria, UK (Parkin et al., 1999), the subsurface time-varying head data at the bottom of the plot for the sand layer were known from borehole measurements and was incorporated into the simulation.

The number of categories for lateral head boundary conditions is specified in VS11. The elements which have a lateral head boundary condition are given the number 4 in VS14 and the category type for each element is specified in VS15. For each category type the number of soil or aquifer layers with lateral head boundary condition are specifed in VS16a and the layer numbers specified in VS16b. In an LHB file the time-varying head data is input for each layer in each category type. The time-varying data is input in breakpoint format (see Section 10 for details of breakpoint format).

8.4.3 Head Gradient Data

Lateral head gradient data is used to specify the head gradient at any layer for any element in the catchment. Thus in the SHETRAN simulation of a hillslope plot in West Cumbria, UK (Parkin et al., 1999), the subsurface time-varying lateral head gradient at the sides of the plot were estimating in the sand layer by interpolation from borehole measurements. These were included in the simulation and enabled water in the simulation to flow in and out of the sides of the plot.

The number of categories for lateral head gradient boundary conditions is specified in VS11. The elements which have a lateral head gradient boundary condition are given the number 5 in VS14 and the category type for each element is specified in VS15. For each category type the number of soil or aquifer layers with lateral head gradient boundary conditions are specifed in VS16a and the layer numbers specified in VS16b. In an LGB file the time-varying head gradient data is input for each layer in each category type. The time-varying data is input in breakpoint format (see Section 10 for details of breakpoint format).

8.5 Flow in/out of the base of the catchment

8.5.1 Flow Data

The standard SHETRAN boundary condition for the base of a catchment is that there is no flow. However, in some cases the base of the simulated catchment is not an impermeable layer, for example, there may be flow to or from a deep aquifer. These flows (m^3/s) in or out of the base of the catchment can be specified for any element in SHETRAN.

The number of categories for which there are base flow boundary conditions are specified in VS11. The elements that have a base flow boundary condition are given the number 7 in VS17 and the category type for each element is specified in VS18. In a BHB file the time-varying flow boundary data is input for each category type. The time-varying data is input in breakpoint format (see Section 10 for details of breakpoint format).

8.5.2 Head Data

Head data at the base of the catchment is used to specify if there is a fixed head for any element at the base of the catchment. In the SHETRAN simulation of a hillslope plot in West Cumbria, UK (Parkin et al., 1999), the whole of the base of the catchment is specified as having a head of –1m.

The number of categories for which there are head boundary conditions at the base of the catchment are specified in VS11. These elements which have a head boundary condition are given the number 7 in VS17 and the category type for each element is specified in VS18. In a BHB file the time-varying head boundary data is input for each category type. The time-varying data is input in breakpoint format (see Section 11 for details of breakpoint format).

8.5.3 Free Drainage

Free drainage at the base of the catchment can be specified for any element. This is achieved by specifying in VS11 the number of categories for free drainage boundary. The elements that have a free drainage boundary condition are given the number 8 in VS17 and the category type for each element is specified in VS18.

Section 9 - Snowmelt (Optional)

9.1 Snowmelt Data

9.1.1 General

The accumulation of a snowpack and its melting has an important effect on the hydrology of a catchment. If the snowmelt component is being used there is considered to be snow in SHETRAN when the air temperature is below 0°C. There are then two methods that simulate the meting of the snow, the degree day factor and the energy budget method.

9.1.2 Degree-day Factor

The degree-day factor is the simpler of the two methods used to calculate snowmelt. The method relies on the fact that of all the meteorological variables the air temperature is usually the most highly correlated with the snowmelt rate (Zuzel and Cox, 1975). The snowmelt then depends on the air temperature (there is snowmelt if the temperature is above 0°C), the degree-day factor and the specific gravity of the snow (usually around 0.1 in new snow and increasing as the snow gets older). The degree-day factor is an empirical factor that varies considerably between sites, depending for example, on the vegetation, slope, aspect and weather patterns. Values of the degree-day factor for a variety of sites are given in Morris (1985, p159). Martinec (1975, p91) shows that modifying the degree-day factor to take into account the snow density could improve the simulation. Care must be taken with the units, those in Morris (1985) are in mm of water day^{-1} $°C^{-1}$, those in Martinec (1975) are in cm of water day^{-1} $°C^{-1}$ and those in SHETRAN are in mm of snow s^{-1} $°C^{-1}$. To use the degree-day factor a meteorological data file (MED) must be available (see 5.1) which must contain the air temperature data (other data in this file is not used in the snowmelt component, although it may be required for the evapotranspiration component).

9.1.3 Energy Budget Method

The energy-budget method is the more complex of the two methods used to calculate snowmelt. It is intended to be used when full meteorological data is available (see 4.1) as it uses this information to calculate the following fluxes to and from the snowpack: net radiation, heat gained by convection from the air, heat gained from condensed vapour, heat gained from precipitation and heat gained from the underlying ground. The contribution of each of these fluxes for a variety of sites is collated in Kuusisto (1986). The aerodynamic resistance, zero plane displacement, and anemometer height are needed for the snowpack, see Appendix C3 for details. The meteorological data file (MED) must be available (see 4.1) and there must be data for the precipitation, net radiation, windspeed, air temperature, slope of the saturation vapour pressure/temperature curve and vapour pressure deficit of the air. Finally, the default specific gravity of the snow and the initial snow temperature must be specified.

9.1.4 SHETRAN Line numbers

The choice of the degree-day factor or the energy budget method is specified in SM4 (in the SMD file). If the degree-day factor is chosen the value for the factor and the specific gravity of the snow are also specified in SM4. If the energy budget method is chosen the initial snow temperature and the specific gravity of the snow are also specified in SM4. The energy budget method also requires that the aerodynamic resistance, zero plane displacement, and anemometer height for the snowpack are specified in SM6. The SHETRAN element number for each of the meteorological stations must also be specified in SM6b for the energy budget method.

9.2 Initial Snowpack Depth

The snowpack depth at the start of a simulation should be measured, however, in many cases there is not a snowpack and the depth is zero. If the snowpack depth at the start of the simulation is zero or the depth of the initial snowpack is uniform this is specified in SM4 and the depth (either 0 or the measured value) is input in SM6. If there is a spatially-varying initial depth this is specified in SM4 and the snowpack depth (m) is specified for every element in SM10 and SM11.

9.3 Initial Snowpack Density

The specific gravity of the snow is the required measurement in SHETRAN for the snowpack density. If there is a uniform initial snowpack a uniform initial specific gravity must be specified in SM4. If there is a spatially-varying initial snowpack, a spatially-varying initial specific gravity must be specified in SM13 and SM14.

9.4 Measured outlet discharge for calibration and validation

In order to test the performance of the snowmelt component it is necessary to obtain the outlet discharge data for a catchment with a period that contains snowmelt (see 1.5 and Section 6 for details of normal calibration and validation procedures). Bathurst and Cooley (1996) used the snowmelt component of SHETRAN in simulations of the Reynolds Creek catchment, Idaho, USA for a two week period in which there was snowmelt. Both the energy budget and the degree-day factor for snowmelt were considered. Using the energy budget method measured values were used and calibration of the other parameters was performed within physically realistic values, this produced a good comparison between the simulated and measured discharge at the outlet. Using the degree-day factor calibration also produced a good comparison between the simulated and measured discharge at the outlet, however, the calibrated value of the degree-day factor was relatively large compared with measured values.

9.5 Measured snow depth for calibration and validation

More detailed calibration and validation of the snowmelt component can be obtained by comparing the simulated and measured snow depths throughout a catchment.

Section 10 - References

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Appendix A – Library of Soil Parameters

Soil Type[1]	Saturated Water Content[2]	Residual Water Content[3]	Saturated Conductivity (m/day)[4]	vanGenuchten- alpha (/cm)[3]	vanGenuchten-n[3]
Clay (20% Sand, 60% Clay)	0.544	0.326	0.014	0.458E-2	1.443
Silty Clay (10% Sand, 40% Clay)	0.529	0.212	0.019	0.654E-2	1.531
Silty Clay Loam (10% Sand, 27% Clay)	0.507	0.144	0.036	0.724E-2	1.608
Silt Loam (10% Sand, 10% Clay)	0.452	0.093	0.163	0.515E-2	1.681
Clay Loam (35% Sand, 27% Clay)	0.489	0.153	0.055	0.923E-2	1.657
Sandy Silt Loam (35% Sand, 10% Clay)	0.434	0.086	0.317	0.838E-2	1.587
Sandy Clay (52% Sand, 40% Clay)	0.499	0.233	0.029	1.069E-2	1.879
Sandy Clay Loam (65% Sand, 24% Clay)	0.461	0.167	0.103	1.236E-2	2.071
Sandy Loam (65% Sand, 10% Clay)	0.412	0.098	0.622	1.441E-2	1.736
Loamy Sand (85% Sand, 6% Clay)	0.370	0.075	1.467	1.986E-2	1.793
Sand (92% Sand, 5% Clay)	0.352	0.066	5.040	2.296E-2	1.847
Peat[5]	0.910	0.319	0.464	1.2E-2	1.536

Notes:

1. The Soil Types are calculated using central values of the British textural Classes. These are shown on Figure 1.

2. The %sand and %clay in the soil types are applied to the Saxton Curves (Saxton et al. 1986). These produce values for the saturated moisture content and the soil water potential/moisture content curves.

3. The soil water potential/ moisture content curves and the saturated moisture content are applied to the van Genuchten equations (van Genuchten 1980). This produces values for the van Genuchten parameters: alpha and n, together with the residual moisture content.

4. Saturated hydraulic conductivities are given for all the soil types in Rawls et al. (1982). Unfortunately these are for the US textural classes which do not exactly correspond with the British ones.

5. the Peat values are taken from the Tyne catchment for the Winter Hill OM2-OM4 horizons (10cm-120cm)

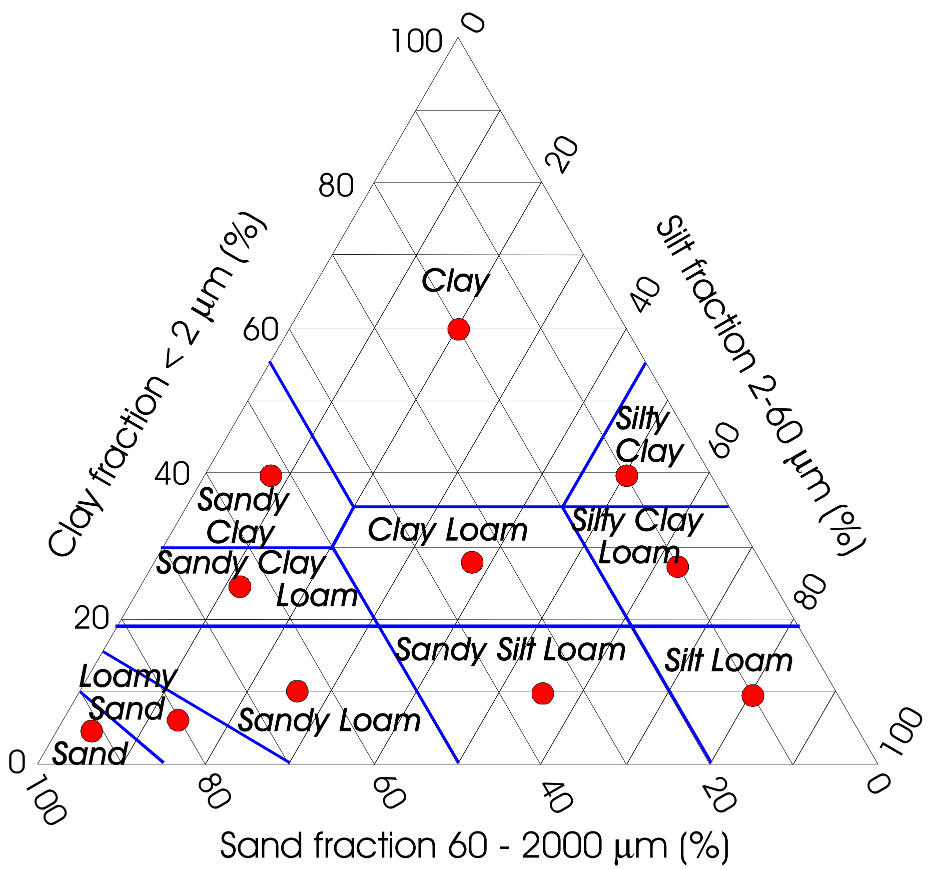

Figure 10 – Particle Size Classes and the position of the soil types in these classes

Appendix B - Library of Vegetation Parameters

Appendix B1 – Canopy and Leaf Parameters

Vegetation	Canopy Drainage[1]		Canopy Storage	Vegetation cover indices	
	CK(mm s^{-1})	Cb (mm^{-1})	CSTCAP(mm)	PLAI	CLAI
Arable	1.4E-5	5.1	1.5	1.0	6.0
Bare ground	0	0	0	0	1.0
Grass	1.4E-5	5.1	1.5	1.0	6.0
Deciduous Forest	1.4E-5	5.1	5.0	1.0	6.0
Evergreen Forest	1.4E-5	5.1	5.0	1.0	6.0
Shrub	1.4E-5	5.1	1.5	1.0	3.0
Urban	1.4E-5	5.1	0.3	0.3	1.0

A review of temperate plant parameter values can be found in Breuer et al. (2003). Values for the canopy storage and vegetation cover indicies are based on this paper. Values of Ck and Cb values are taken from the SHETRAN simulation of the Tyne catchment. (Dunn and Mackay, 1995)

The values included here for CLAI are their maximum values during the year. Some values, particularly arable and deciduous land, vary through the year and time varying values should be incorporated into SHETRAN.

Appendix B2 – Root Density Function

The suggested root density function (RDF) for standard vegetation types is given below. The function depends on the depth below ground, in SHETRAN it is input according to the proportion of roots in each cell. It is important that the rooting depth is not bigger than the soil depth.

Vegetation	Total rooting depth	Depth of cell below Ground														
		0.1	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1.0**	**1.2**	**1.4**	**1.6**	**1.8**	**2.0**
Arable	0.8	0.31	0.228	0.17	0.1	0.072	0.06	0.04	0.02							
Bare Ground	0.1	1.0														
Grass	1.0	0.25	0.18	0.15	0.12	0.1	0.08	0.06	0.03	0.02	0.01					
Deciduous forest	1.6	0.178	0.144	0.126	0.108	0.094	0.08	0.066	0.052	0.04	0.027	0.04	0.027	0.018		
Evergreen forest	2.0	0.13	0.12	0.11	0.1	0.09	0.08	0.07	0.06	0.05	0.03	0.06	0.04	0.03	0.02	0.01
Shrub	1.0	0.25	0.18	0.15	0.12	0.1	0.08	0.06	0.03	0.02	0.01					
Urban	0.5	0.4	03	0.2	0.07	0.03										

Appendix B3 – Evapotranspiration Parameters

If potential evaporation (E_{rc}) is being used in SHETRAN (see 3.10.4) then the actual / potential evapotranspiration (E_a/E_{rc}) function is necessary. This is given below for standard vegetation types, for forests see the note at the end of Appendix B3.

For forest:

Soil moisture Tension (m)	Actual /Potential Evapotranspiration(E_a/E_{rc})
-1000	0
-150	0.05
-50	0.2
-20	0.5
-10	0.8
-1	1.0
-0.1	1.0

For arable and grassland:

Soil moisture Tension (m)	Actual /Potential Evapotranspiration(E_a/E_{rc})
-1000	0
-150	0.03
-50	0.12
-20	0.3
-10	0.48
-1	0.6
-0.1	0.6

For shrub, urban and bare soil:

Soil moisture Tension (m)	Actual /Potential Evapotranspiration(E_a/E_{rc})
-1000	0
-150	0.02
-50	0.08
-20	0.2
-10	0.32
-1	0.4
-0.1	0.4

Note, The maximum (E_a/E_{rc}) ratio given here for forest is 1.0. However, for forests the maximum value is often similar to grassland. However, overall evapotranspiration is higher than for grassland due to the higher intercepted evaporation from the canopy (as a result of lower aerodynamic resistance). Thus in SHETRAN simulations (which do not simulate the very high intercepted evaporation using this method, as the maximum intercepted evaporation rate is equal to PE) a high value for the crop coefficient and a high canopy storage capacity is often used to try and compensate. See Appendix C.

Appendix C – The Penman–Montieth and Penman equations

Appendix C1 – Definitions

Care must be taken when reading any book or paper concerning evaporation concerning the definitions, there appears to be no standard. The following definitions are taken from Shuttleworth (1993).

E_p – Potential evaporation of water evaporated from an idealized, extensive free water surface under existing atmospheric conditions.

E_{rc} – Reference Crop evaporation from an idealized grass crop with a fixed crop height of 0.12m, an albedo of 0.23 and a surface resistance of 69 s/m. (equivalent to a crop of short grass, not short of water).

Equally care must be taken over the units

Appendix C2 – The Penman-Monteith Equation

The Penman-Monteith has been developed from first principles based on the physics of the processes (Monteith, 1965)

$$E = \frac{R_n \Delta + \frac{\rho c_p \ \delta e}{r_a}}{\lambda[\Delta + \gamma(1 + \frac{r_c}{r_a})]} \qquad \text{(Eqn. C1)}$$

Where:

E = potential evapotranspiration for a particular crop ($kg/m^2/s \equiv mm/s$)

R_n = net radiation (W/m^2)

Δ = rate of increase with temperature of the saturation vapour pressure of water at air temperature (mb/°C)

ρ = density of air (kg/m3)

c_p = specific heat of air at constant pressure (J/Kg/°C)

δe = vapour pressure deficit of the air (mb)

r_a = aerodynamic resistance to the transport of the water vapour from the canopy to a plane 2m above it

r_c = canopy resistance to water transport from some region within or below the transpiring surface to the surface itself

λ = latent heat of vaporization (J/Kg)

γ = psychrometric constant (mb/°C) given by

$$\gamma = \frac{p\, c_p}{\sigma \lambda} \qquad \text{(Eqn. C2)}$$

Where:

p = atmospheric pressure (mb)

σ = ratio of density of water vapour to density of air (appox. 0.622)

Taking c_p = 1003 J/Kg/°C, $\lambda = 25 * 10^5$ J/Kg and p = 1016 mb, then γ = 0.655 mb/°C

Bevan (1979) showed that the potential evapotranspiration is very sensitive to the aerodynamic and canopy resistances and these are now considered here. The canopy resistance r_c referred to here is the bulk stomatal resistance of the whole plant canopy. It also takes into account the dryness of the soil. Equations for calculating the value for wet soils depending on the leaf area index have been developed and typical values are given in (Burman and Pochop, 1994, pp89-90 and 147-148). The aerodynamic resistance r_a depends on the friction of air flowing over the vegetation surface. There are various methods used to calculate the value (Burman and Pochop, 1994, pp87-90) but all have a significant empirical component. One method that can be used directly in SHETRAN is to calculate the value directly from the wind velocity profile using the logarithmic boundary layer equation,

$$r_a = \frac{1}{\kappa^2 u}[\ln(\frac{z-d}{z_0})]^2 \qquad \text{(Eqn C3)}$$

Where;

K = von Karman constant (= 0.41)

u = windspeed 2m above the vegetation (m/s)

z = height of the anemometer (2m above the height of the vegetation)

d = zero plane displacement (assumed to be 0.75 * height of the vegetation)

z_0 = roughness height (assumed to be 0.1 * height of the vegetation)

Values for the zero plane displacement and the roughness height are taken from those suggested by Rutter et al. (1971).

When the canopy is wet, evaporation of the water on the plants surface takes place rather than transpiration from inside the leaves. As the stomata as no longer resisting evaporation the canopy resistance r_c = 0. This reduces Equation C1 to the following:

$$E = \frac{R_n\Delta + \frac{\rho c_p \, \delta e}{r_a}}{\lambda[\Delta + \gamma]} \qquad \text{(Eqn. C4)}$$

Thus the intercepted evaporation for different vegetations depends only on the aerodynamic resistance. With taller vegetation there is an increase in roughness height and a decrease in the aerodynamic resistance from approximately 50 for grass to 5 for forests. This produces considerably higher intercepted evaporation in forests than in grassland.

Above open water there is also no canopy resistance and $r_c = 0$. Eqn C4 can then be modified to give the value for the potential evaporation E_p (Shuttleworth, 1993). This requires that the net radiation term incorporates the energy advected to the water and an appropriate form of the aerodynamic resistance term is used with standardized measurements for wind speed, temperature, humidity and roughness heights. This produces an equation of the same form as the Penman equation (Appendix C3).

Comparisons can be made between the evaporation rate for a wet canopy with the canopy resistance set to zero (Eqn C4) and the transpiration rate with a typical value of canopy resistance (Eqn C1), see Rutter (1975). It can be seen that when r_c and r_a are of a similar size, as they are in grassland communities then the evaporation from the wet canopy will be similar to the transpiration rate. However, in forests r_c is an order of magnitude greater than r_a, water will then be evaporated from the wet canopy at 3 to 5 times the transpiration rate. This is important in the next section when the evaporation calculated using Penman's evaporation is discussed.

Appendix C3 – The Penman Equation

The Penman equation is a special case of the Penman-Monteith equation. Parts of it are physically based on the same physics, however, parts of it are based on empirical relationships. The basic equation is of the form:

$$E = \frac{R_n\Delta + \gamma f(u)(e_s - e)}{\lambda[\Delta + \gamma]} \qquad \text{(Eqn C5)}$$

where

e_s = saturated vapour pressure (mb)

e = vapour pressure (mb)

f(u) is an empirical function of the wind speed u, 2 meters above the vegetation, of the form:

$$f(u) = a + b\,u$$

where a and b are constants. Workers have introduced a wide variety of values for a and b to take into account the climate and the time of year which has brought some uncertainty into the exact definition of the Penman equation. Details of some values are given in (Burman and Pochop, 1994, pp80-86).

If R_n is measured over open water (including the energy advected to the water body) and a suitable value of the wind speed function is used (Suttleworth, 1993,p4.15), then this gives the value of the potential evaporation, E_o. If R_n is measured over grass (including the measured soil heat flux) and includes a suitable value of the wind function (Suttleworth, 1993,p4.150), then this gives the value of the reference crop evaporation, E_{rc}.

Thom and Oliver (1977) also showed that within the Penman equation there is an implicit roughness length (z_0) of 1.4mm and errors in the Penman equation cancel out in crops in which r_c/r_a ~ 1.4, this is for crops with smooth surfaces such as short grass.

In forests as discussed in Appendix C2 the r_c/r_a is considerably larger than 1.4 and hence the Penman equation is not valid. The result of this is that if reference crop evaporation rate is used for tall vegetation (e.g. forest), this rate considerably underestimates the evaporation of precipitation intercepted by the canopy of tall vegetation.