Institute of Hydrology

Natural Environment Research Council

Modelling Climate Change Impacts on Biogeochemical and Ecological Systems: Core Model Project

2nd progress report, for the year to November 1992.

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Summary

The impacts of climate change core model project at IH has now run for two years. During the second year research has concentrated on a number of key issues summarised below. Each of these summary points relates to a detailed chapter within the main report.

Two UK datasets have been obtained and added to the existing datasets available for use within the project. The new datasets are the UK gauged catchment boundaries and England and Wales river network. Problems of validation on such large datasets are highlighted and discussed with reference to model simulations.

Following consideration of the required resolution of climate data an investigation was undertaken to assess the appropriateness of using stochastic rainfall generation for use in climate change impacts models. Two models were constructed, a first order two state Markov chain and a first order five state Markov chain. Both models simulated the magnitude and frequency of rain events well compared with observed data. It was not clear, however, how the parameters of the five state model should be perturbed in line with predicted future climate scenarios. The two state model was utilized in all further model studies.

Stochastically generated rainfall scenarios were generated and applied to a physically based, semi-distributed hydrological model (TOPMODEL) to test the validity of using the model as a tool for assessing impacts on streamflows and catchment water storages. TOPMODEL predictions indicate that hourly resolution rainfall data is required to determine significant differences in predicted streamflow regimes and catchment water storage. Very little difference was predicted in the percentage of time the catchment was saturated between the 'wet' and 'dry' future climate scenario. This is also partly due to the inability of the two state stochastic rainfall generator to simulate the observed persistence in rain events.

The use of TOPMODEL for use at a regional level of application, as part of the overall linked model framework, is investigated. Results show that TOPMODEL is inappropriate as a regional model unless a DTM on a grid scale of, at least, 100 m by 100 m is available.

A grassland vegetation model has been developed driven by light and temperature and with requirements for nitrate, as the sole nutrient, and water. The model is applied to the Monachyle Glen catchment at Balquhidder, Scotland using observed weather data. The effect of a 3 °C rise in mean temperature and a doubling of CO_2 is investigated. Simulation results were similar to observed data. The experiments at elevated CO_2 showed that smaller canopy sizes are produced, but the rate of canopy formation increases.

A hydrological model was applied to the Balquhidder catchment, as a step toward future assessment of the suitability of the model structure for the linked climate change model. The simulation achieved a reasonable fit although spikes in observed stream flow are generally under estimated. This leads to an over estimation in the amount of water in the upper soil reservoir and consequently the potential for overestimation in the water supply to the vegetation model when linked.

The grassland model was linked to a simple nitrate model as an exercise to highlight the problems involved in coupling the feedback mechanisms between the models. Problems of time scale were resolved.

The methodology of linking the grassland, nitrate and hydrochemical models is investigated. Some of the potential difficulties in incorporating feedbacks between the models are discussed as well as the necessary underlying assumptions.

A menu system has been designed to apply climate change scenarios to individual and linked models developed within the project and to simplify the application of models to UK catchments. The menu system is described and future developments are specified.

A recent NERC TIGER IV initiative is described which has potential links to the DOE core model project in that it focuses on the development of a strategy for quantifying the impacts of climate change on hydrological systems within the UK uplands. The project is specifically using and developing the hydrological model IHACRES to enable parameter estimation from catchment physical attributes.

Finally, future work for the final year of the existing project is outlined together with any potential future problems relating to that work. A longer term perspective is also given in the form of further research areas which will be necessary to realise the full extent of the climate change impacts assessment methodologies developed.

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1) Introduction

1.1) Overview

This report summarises the work completed at the Institute of Hydrology during year two of the Department of the Environment Core Model programme. The research reported is a component of a wider UK climate change impacts study involving the Institute of Terrestrial Ecology, (ITE) Monkswood (biological modelling) and with the Climatic Research Unit (CRU), University of East Anglia (LINK project - provision of climate change data). These groups report separately to DOE although close communication between the three groups has been maintained throughout the year. In particular, with respect to the core model requirements for climate data generated at the Hadley Centre during the transient GCM runs. To this end, IH project staff attended a workshop held at CRU and presented data requirements. The question of provision of baseline climatology data and perturbed climate data was discussed although has not yet been resolved satisfactorily. This communication will continue throughout the next year, particularly as results from climate change scenario model runs are made at the Hadley Centre and data becomes available from CRU. Potential research links between ITE and IH will be continuously reviewed.

The focus of IH activities within the Core Model programme is the development of a computer modelling framework to assess the likely impact of climate change on the the biogeochemistry of UK ecosystems. A wide range of modelling and database activities have taken place in this second year to achieve this aim. In particular, the various sub-models which will be brought together within a final linked model framework have been developed and tested. Some of these sub-models have proved inadequate for this purpose but the lessons learnt from these studies provide useful theoretical and practical considerations for the use of models in future impacts related studies. The development of one of the sub-models, the grassland vegetation model, has taken place entirely at the University of Sheffield, Department of Animal and Plant Sciences, under a sub-contract. Their work is, therefore, included in this report.

This work on the development, calibration and validation of component sub-models has formed the bulk of IH research effort. At the same time work has continued in the development of the interface between GIS technology, database and the models. A number of extra UK datasets have been added to those currently available to the Core Model project. Software to enclose and run the linked sub-models is being developed as a 'user-friendly' menu driven system with full screen graphics facilities.

In the course of the year IH staff have initiated important national and international links with other researchers in the same field. Andrew Eatherall presented a poster paper at the European Geophysical Society Conference in Edinburgh (April 1992) describing the philosophy behind the linked model. Paul Whitehead presented similar material at a GENEVER meeting in Bedford (March 1992). Andrew Eatherall and William Sloan delivered seminars at the Woods Hole Centre for Ecosystem Research and University of New Hampshire (September 1992) and in so doing established important working links with these influential groups. Also, Alan Jenkins strengthened links with the Ecosystem Research group at the University of Virginia during a working level visit (September 1992). As a result of these links we have obtained databases for model calibration and validation as well as, perhaps most importantly, critical review of our models and methods.

A new project recently started at IH has potential links with the Core Model project. Under the NERC Terrestrial Initiative in Global Environmental Research (TIGER) programme, the potential use of a hydrological model (IHACRES) as a regional tool is being explored. If this model can be parameterised from relationships with catchment physical attributes there exists the potential that this could be linked to the Digital Terrain Model (DTM) and brought within the framework of the linked model. IH also undertakes research on the hydrological impact of climate change for DOE Water Directorate and NRA.

1.2) Overall Project Objectives

The Core Model research programme at IH has three main objectives;

- To provide core models for predicting the impacts of climate change on biogeochemical and ecological systems.
- To provide models which run for both equilibrium and transitional climates.
- To couple the models with a GIS to examine the impacts spatially across the UK.

1.3) Project Rationale - Climate Change Predictions

The potential for future climate change has been estimated by a number of groups, each climate change amendment refining earlier ones. The 1991 climate change impacts review group [30], proposed a 'business-as-usual' scenario of greenhouse gas emissions that would result in a rise of 1.4 °C in the UK summer temperature, a mean winter season temperature rise of between 1.5 °C and 2.1 °C, an average precipitation increase of 5% during winter and the a 20cm rise in global sea-level.

Subsequently, the 1992 IPCC report [13,24] reports the predicted effect of different emission scenarios on world climate by the year 2100. These results were produced using coupled GCM's. The business-as-usual scenario produces a sea-level rise of 2-4 cm per decade with a 0.3°C per decade temperature increase over the next century. This is similar to the 1991 IPCC assessment [30]. The 1992 IPCC 'high climate sensitivity' scenario, however, predicts a 4°C global mean temperature change, whereas the 'low climate sensitivity' scenario predicts a global mean temperature change of 2°C, with a 'best climate sensitivity' of approximately 3°C.

Wigley and Raper [32] have taken the same 1992 IPCC scenarios and made further predictions incorporating extra factors in the coupled GCM's including; the cooling effect caused by the production of sulphate aerosols from sulphur dioxide emissions, the potential cooling effect of stratospheric ozone depletion and the possible increased uptake of carbon dioxide by the biosphere as carbon dioxide concentrations increase. These predictions suggest a global-mean warming of 2.5 °C and a global-mean sea-level rise of 48 cm from 1990 to

2100. This gives an average warming rate of 0.2 °C a decade, half that of the 1992 IPCC report but still greater than any natural variability in climate change over the last 5000 years.

These many estimates of possible change in climate will have far reaching effects on all aspects of UK ecosystems. The most important questions are whether these effects can be quantified and whether the biogeochemistry of UK ecosystems is sensitive to these apparently small differences in model predictions. This latter point is clearly important in the light of recent international agreements and discussions calling for reductions in emissions of greenhouse gases to limit environmental effects. The Core Model project at IH (ICE -Impact of Climate change on Ecosystems) will attempt to address these questions using a model based approach. A modelling framework for climate change impact is mandatory in the light of this uncertainty in the degree of change and given the need for scenario assessments.

2) Datasets

Two UK datasets have been added to the existing project datasets during the past year. The existing UK project datasets [11] include; HOST, Land use, DTM and Hydrometric areas (Figures 1-4). Added to these available datasets are the UK gauged catchment boundaries (Figure 5) which correspond to the Surface Water Archive (SWA) held at the Institute of Hydrology [14] and the England and Wales river network database. The River network was digitised at 100 m resolution and it is impractical to show the whole network. Figure 6 shows an example of the data as the river network for the Kent group, a hydrometric area in the North West of England. This river data was extracted using the overlay facilities within the Arc/Info GIS. The datasets described above can be accessed via the menu system described in Section 10.

2.1) Validation of datasets

One aspect of utilizing large datasets that has become apparent is that validation is not possible and thus it is necessary to assume that they are error free. Inevitably errors exist in such large datasets (each UK 1 Km^2 dataset consisting of over 250,000 grid squares), some of which can be detected whilst working on the datasets, whilst others may remain undetected. This may lead to problems when applying models at regional and site specific scale, since some erroneous results may occur. Unless the errors in the datasets cause large and obvious errors in the model results, these errors will likely go undetected. Furthermore, as running models becomes more automated, smaller errors within the datasets may be overlooked and become hidden within model results, particularly if the results of the model lie within our perceived expected range. This raises two issues. First, it is necessary to take all precautions to ensure that the datasets being utilised (usually from an external source) are rigorously validated and second, it is important to keep in mind that the results of the model may be based upon inaccurate data, even assuming that the model itself is error free. The datasets used so far will not be screened further for errors within the remit of this project as this is time consuming and out with the overall aims of the project.

UK 1Km HOST Dataset

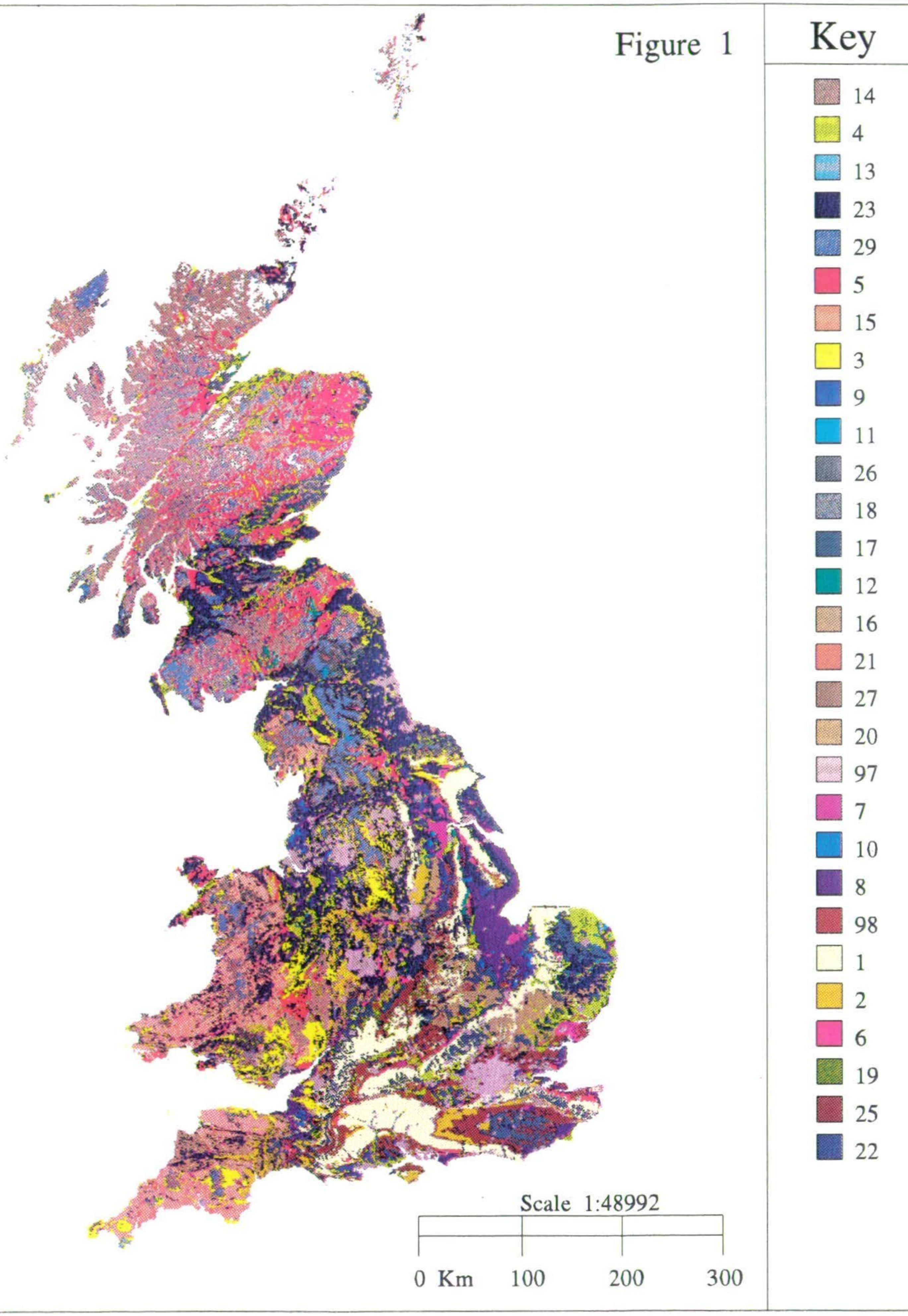


Figure 1

UK 1Km Land Use Dataset

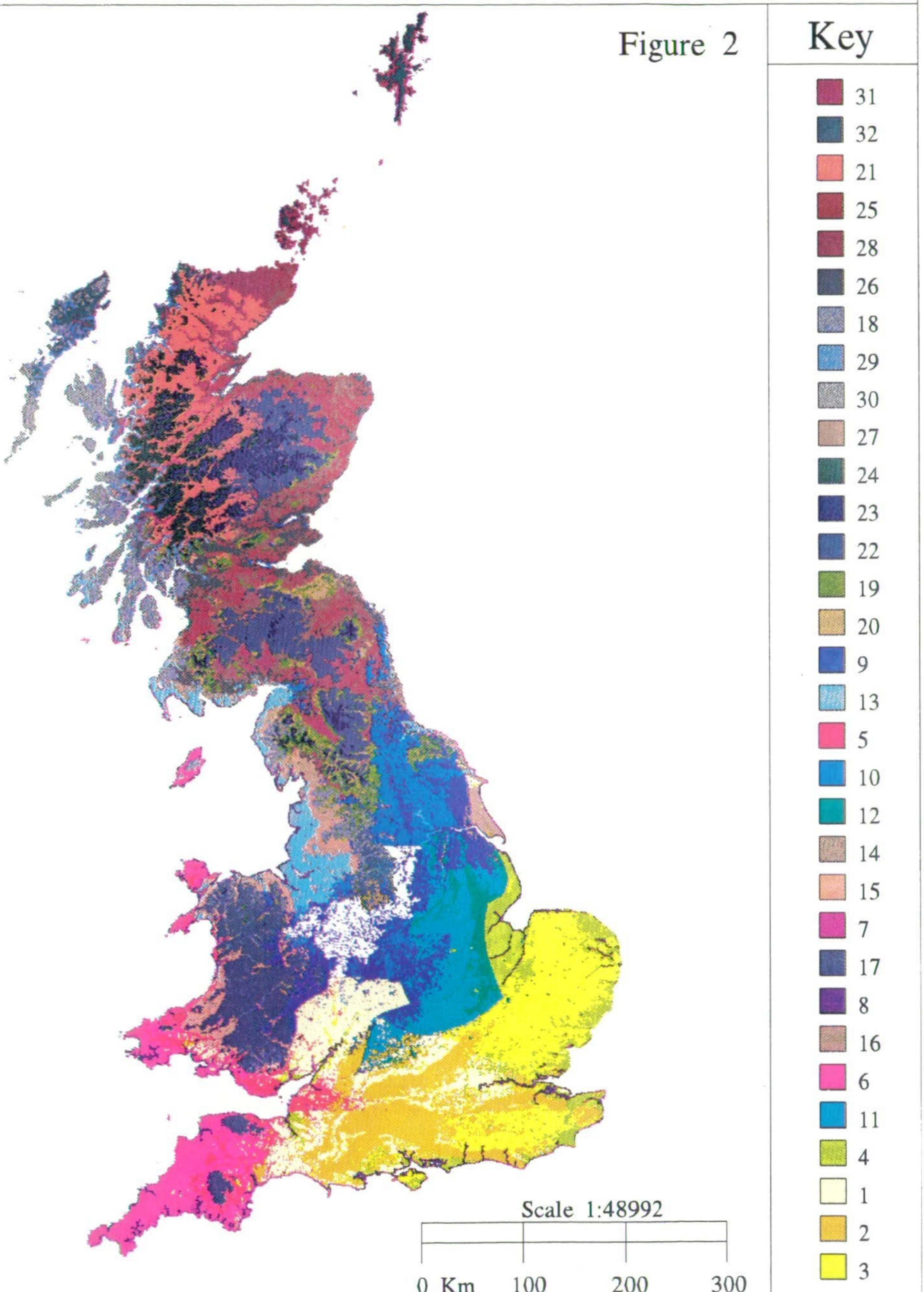


Figure 2

UK 1Km Altitude Dataset

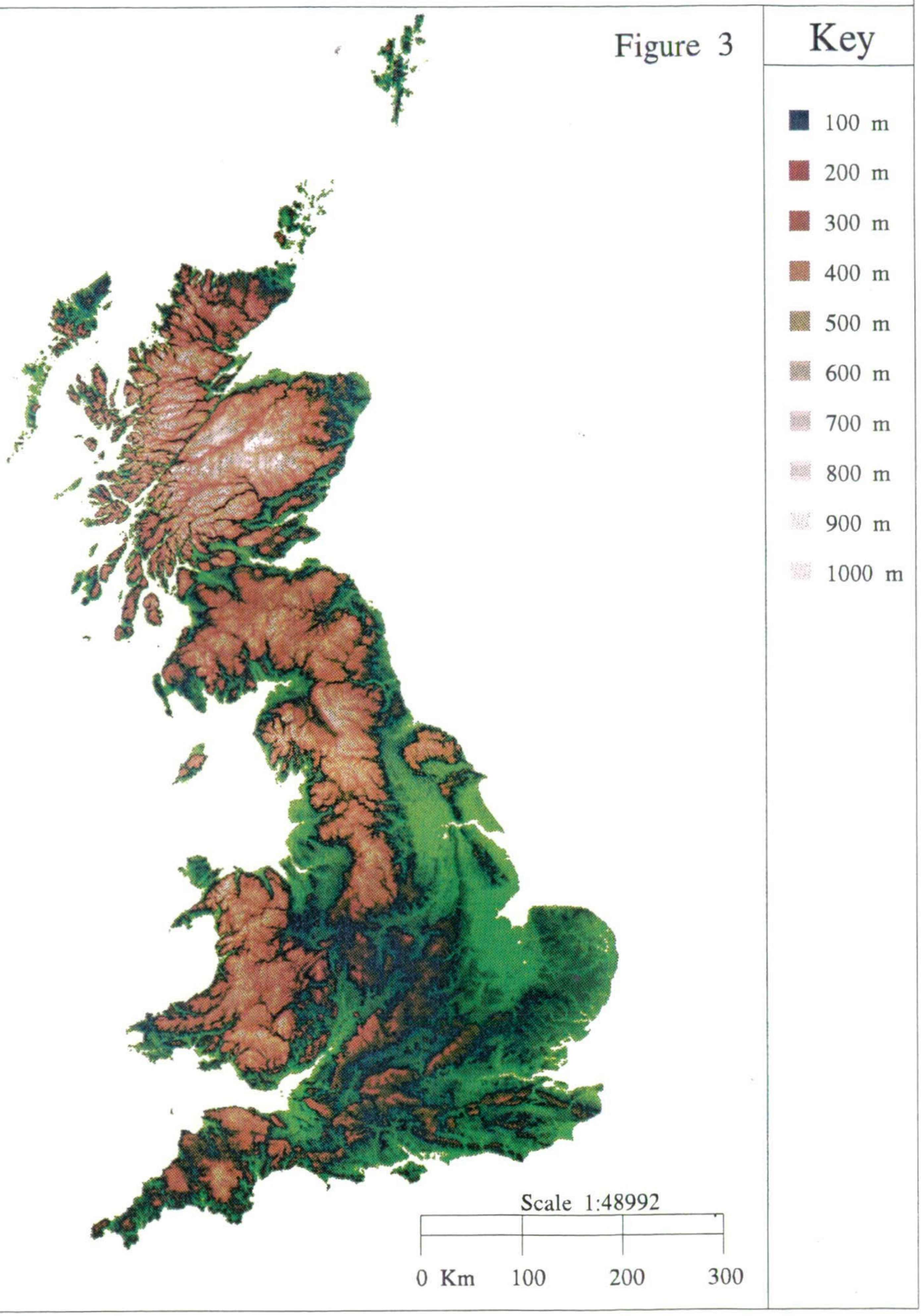
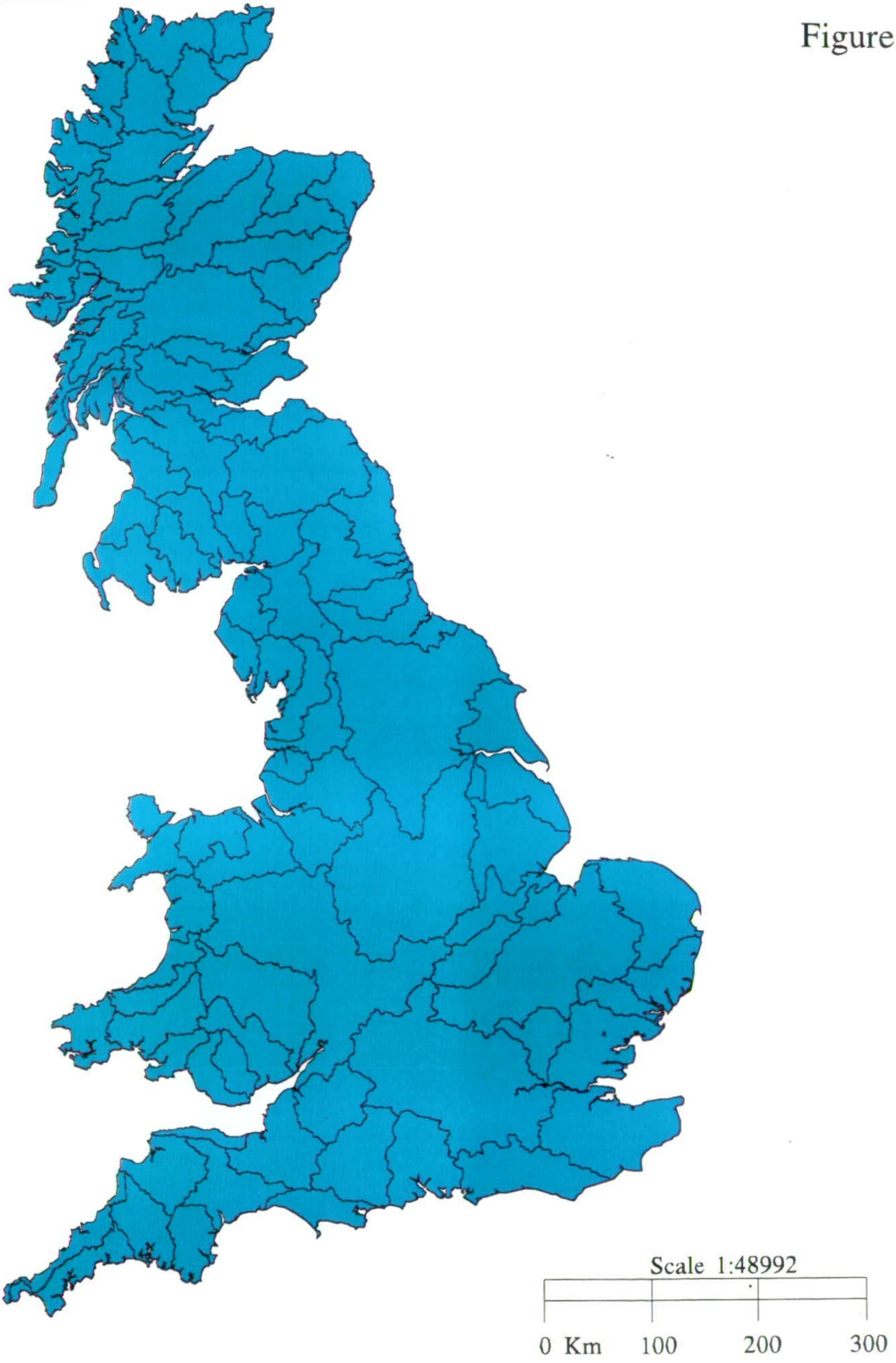


Figure 3

UK Hydrometric Areas

Figure 4



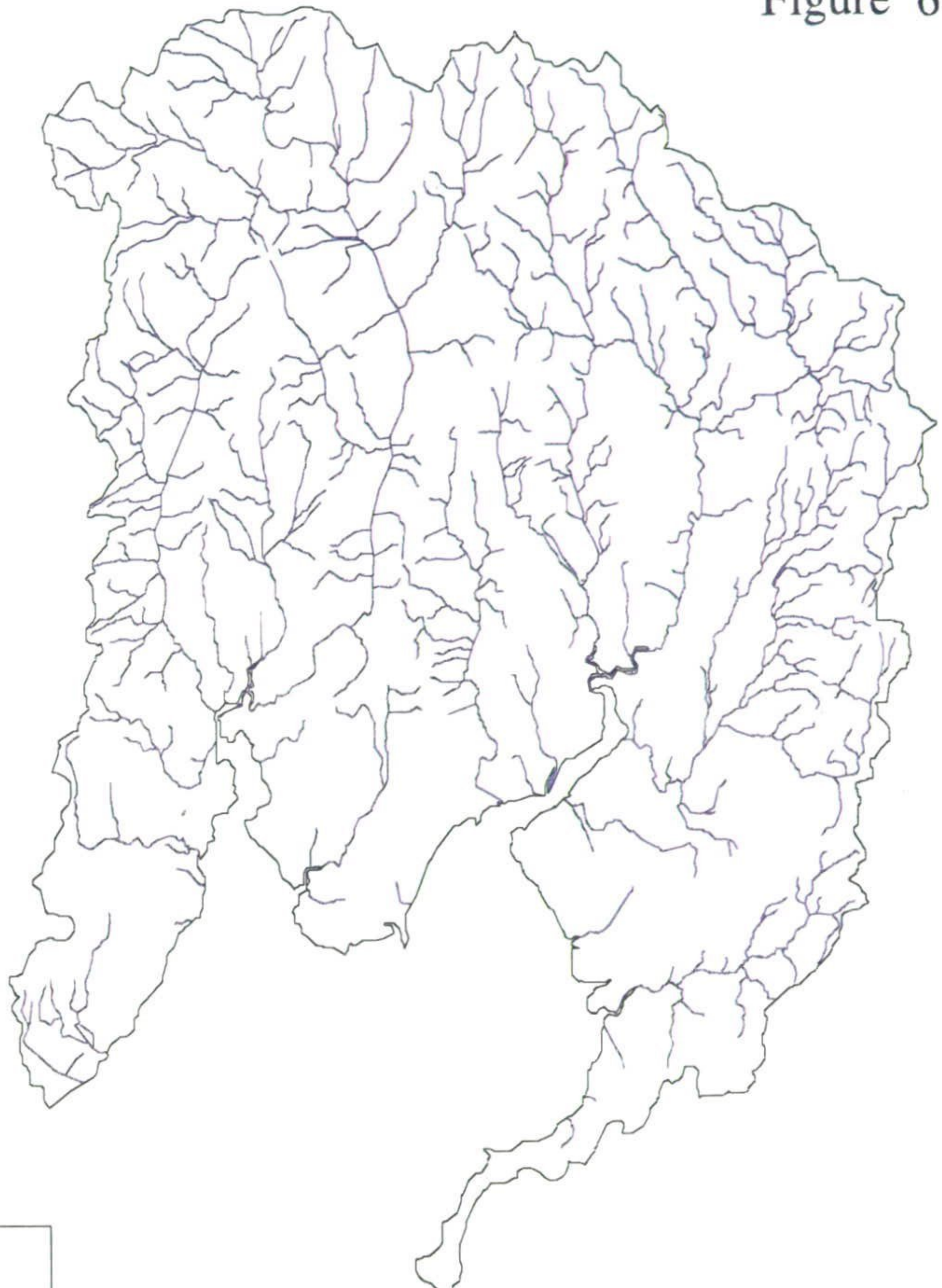
UK Gauged Catchments

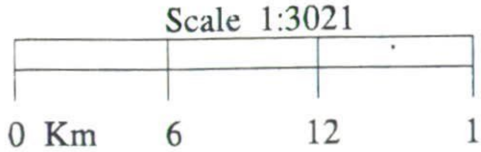
Figure 5

UK River Data

Kent Group

Figure 6





3) Stochastic Rainfall Generation

Climate models are normally applied at a global scale on a coarse spatial resolution. As a result they tend to be poor at simulating some regional aspects of the climate and short term temporal variations in weather. Published results from global climate change models describe future climate scenarios using monthly or yearly statistics [24]. The core models being used in this project will be required to model the responses of systems to climate change on a shorter scale, probably daily. It is, therefore, necessary to extrapolate short term variations in weather at a regional level from these statistics. In particular, for investigating hydrological responses daily or weekly predictions of rainfall are required as a minimum. Stochastic models represent a method for generating rainfall series similar to observed rainfall series according to temporal variation and density distribution. Clearly, such models developed for this project should have parameters which are easily perturbed according to some future climate scenario.

Two stochastic models were considered here. In the first, a first order, two state Markov chain governed the occurrence of wet or dry days. On the days with rain an incomplete gamma distribution was used to describe the amount of rain. The second model used a first order, five state markov chain to describe the occurrence and amount of rain.

The first model is briefly described below and a more complete description of Markov chain theory can be found in statistical texts such as Bailey [2]. The two states of the process are wet or dry. A day is considered to be wet if the total rainfall, areally averaged across the catchment, exceeds 0.05 mm. For a first order Markov chain the probability of a state occurring is conditional on the state of the previous day. These conditional probabilities are called transitional probabilities. Let p_{wd} be the probability that a day is wet given that the previous day was dry, p_{ww} be the probability that a day is wet given that the previous day was wet, and so on. Then the evolution of the process is governed by four transitional probabilities p_{ww}, p_{wd}, p_{dd}, p_{dw}. However,

$$p_{dw} = 1 - p_{ww},$$
$$p_{dd} = 1 - p_{wd}.$$

Therefore the transitional probabilities are fully defined by p_{ww}, p_{wd}.
The incomplete gamma distribution, which describes the amount of rainfall on a wet day has a probability density function (p.d.f.) of the form;

$$f(x) = \frac{x^{\alpha-1} e^{-x/\beta}}{\beta^{\alpha}\Gamma(\alpha)} \tag{1}$$

Thus the evolution of the stochastic model is dependent on four parameters, α, β, p_{ww} and p_{wd}. Seasonal variations in these parameters must be taken into account when generating a rainfall sequence for any year. This can be accomplished using a fourier function or some other periodic function [22], which gives a continuous variation in the parameters during a year. However, since future climate scenarios are normally prescribed by seasonal statistics which do not vary continuously during a year, there is no advantage in having parameters of this type. The seasonal variation, therefore, was incorporated by estimating the parameters for each month. The maximum likelihood estimates for alpha and beta are;

$$\beta = var/\bar{x} \tag{2}$$

$$\alpha = \bar{x}/\beta \tag{3}$$

where $\bar{x}$ is the mean daily rainfall on wet days and var is the variance in daily rainfalls. The estimates of p_{ww} and p_{wd} are given by;

p_{ww} = Number of wet days which follow a wet day/ Number of wet days

p_{wd} = Number of wet days which follow a dry day/ Number of dry days

The second stochastic model is a first order markov chain with five rainfall categories. The first state is that a day is dry. The remaining four states are selected so that each class held approximately 25% of the total number of rain days: the class limits are determined by fitting a gamma distribution to each. A five by five transition matrix was calculated from observed data, showing the probability that a day in state i is followed by a day in state j. Using the rainfall record from the Monachyle catchment at Balquhidder, Scotland, as an example it was found that too few data were available to calculate such a transition matrix for each month and so matrices were calculated for each of the four seasons (December to February, March to May, June to August and September to November).

It is possible in principle to describe the distribution of rainfall magnitudes within a class using a probability distribution fitted to that class's data, but in practice sample sizes are too small for each distribution to be estimated with any confidence. Exact magnitudes were, therefore, determined by interpolating on the distribution function of the gamma distribution estimated from the seasonal rainfall data. Note that the five state model uses parameters estimated on a seasonal basis and the two state uses monthly estimates.

3.2) Comparison of Simulated Rainfall with Observed Rainfall.

The observed rainfall used consisted of eight years of areally averaged, daily rainfall for the Monachyle catchment at Balquhidder in Central Scotland. This was used to estimate the parameters for both stochastic models. Eight years of synthetic data were generated from both models. Statistics of the observed and simulated rainfalls were used to compare the persistence of wet and dry spells and the magnitude of rain events. Figure 7 summarizes the distribution of both simulated and observed rainfall on wet days for each month. The mean rainfall appears to be reasonably well simulated by both models. The variability in rainfall, characterised by the standard deviation, is also well simulated. Table 1 shows the average total rainfall for each season. Both models adequately reproduce the observed averages. The persistence of rain events can be assessed by considering the autocorrelation coefficients for a daily rainfall series. Table 2 shows the autocorrelation coefficients for both models for each season. The observed rainfall exhibits an autocorrelation coefficient of approximately 0.3 for each season for a lag of one day. This reduces to about 0.15 for a lag of four days.

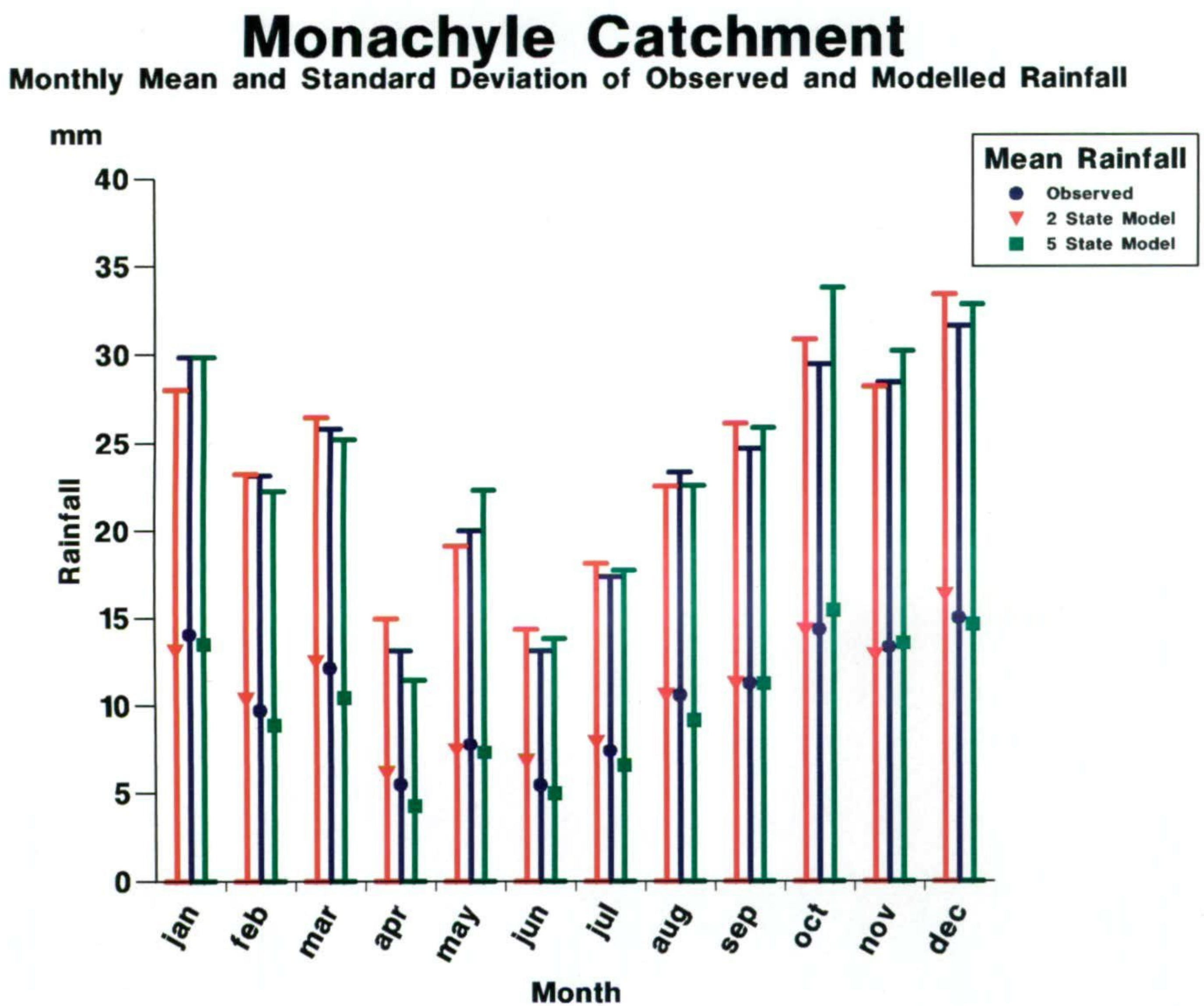

Monachyle Catchment
Monthly Mean and Standard Deviation of Observed and Modelled Rainfall
mm
Rainfall
40
35
30
25
20
15
10
5
0
Mean Rainfall
Observed
2 State Model
5 State Model
jan
feb
mar
apr
may
jun
jul
aug
sep
oct
nov
dec
Month

Figure 7

Table 1 Average Total Rainfall for Each Season

Season	Observed	Two-State	Five-State
DJF	938.0	912.0	797.0
MAM	540.0	543.0	474.0
JJA	468.0	505.0	453.0
SON	923.0	865.0	948.0

The rainfall series produced by the two state model exhibits no significant autocorrelation coefficients. This suggests that the persistence of rain events is poorly simulated by the two-state stochastic model. The five state model simulates the persistence of rain events better than the two state, however, the autocorrelation coefficients are still smaller than observed.

Table 2 Seasonal Correlation Coefficients

Lag	Model	DJF	MAM	JJA	SON
1 Day	Observed	0.323	0.296	0.276	0.303
	2-State	0.077	0.066	0.111	0.089
	5-State	0.267	0.195	0.189	0.177
2 Days	Observed	0.223	0.256	0.187	0.226
	2-State	0.060	0.113	0.070	0.083
	5-State	0.183	0.115	0.111	0.147
3 Days	Observed	0.173	0.211	0.150	0.145
	2-State	0.058	0.043	0.077	0.029
	5-State	0.082	0.024	0.045	0.029
4 Days	Observed	0.152	0.145	0.147	0.109
	2-State	0.064	0.066	0.065	0.029
	5-State	0.082	0.069	0.061	0.053

The stochastic rainfall generation model was constructed in order that the model parameters could be perturbed to comply with some future climate scenario. The effects of perturbing the parameters of the two state model are fairly intuitive. Altering the α and β parameters of the incomplete gamma distribution will change the distribution of rainfall on wet days. Altering the transitional probabilities will change the probability of wet days occurring. For example, if p_{ww} was increased longer wet spells would be more likely.

It is difficult to know how to perturb the parameters of the five-state model. The first state is that a day is dry, the class interval of the other four states is chosen so that each class holds approximately 25% of the total number of rain days. Therefore, the class intervals are dependent on the shape of the incomplete gamma distribution. Hence, they cannot be altered independently. For example, if any of the transitional probabilities were perturbed then the probability of a day's rainfall being in a particular state would be altered. Therefore, the portion of the incomplete gamma distribution pertaining to that state is no longer representative of the distribution of rainfall. Hence, any perturbation of the transitional probabilities would have to be accompanied by a change in the incomplete gamma distribution of rainfall events.

In summary, the magnitude and frequency of rain events is well simulated by both the five state and the two state models. The five state model simulates the persistence of rain events better than the two state model. At present it is unclear how to perturb this model to comply with future climate scenarios and so the two state model has been utilized for detailed analysis of the hydrological sub-model.

3.3) Future Scenarios

To asses the validity of the chosen hydrological model and compare its' performance using the available and generated input data the stochastic rainfall generation model was used to generate three rainfall series. One for the present climate, one for a future wetter climate and the other for a future drier climate. The changes in rainfall for both future scenarios are intended to reflect extreme cases but are arbitrarily chosen. In the dry scenario the mean rainfall on a wet day is presumed to decrease by 15%. The probability of longer dry spells is increased by subtracting 0.1 from the transitional probability of it being wet given that the previous day was dry. In the wet scenario the mean rainfall on a wet day is presumed to increase by 15%. The probability of shorter dry spells is increased by adding 0.1 to the transitional probability of it being wet given that the previous day was dry.

Statistics which summarise the magnitude of rainfall produced by the stochastic model were calculated from eight years of synthetic data (Table 3). The mean rainfall on wet days for each month is smaller for the drier climate than the present climate and larger for the wetter climate, as are the mean rainfall totals for each season.

The percentage of time for which daily rainfalls are exceeded is plotted in Figure 8 for the simulated present climate, two future climate scenarios and observed rainfall. This can be used to compare the magnitude and frequency of daily rainfall. Observed and simulated rainfall under the present climate appear to be fairly similar. The stepped appearance of the observed rainfall exceedance curve is due to the observations being accurate to one decimal place while the simulated rainfalls were calculated to three decimal places. The percentage of time daily rainfalls are exceeded for the simulated future dry climate scenario is significantly smaller than for the present climate and is significantly greater for the future wet climate scenario.

Simulated Rainfall For The Monachyle Catchment

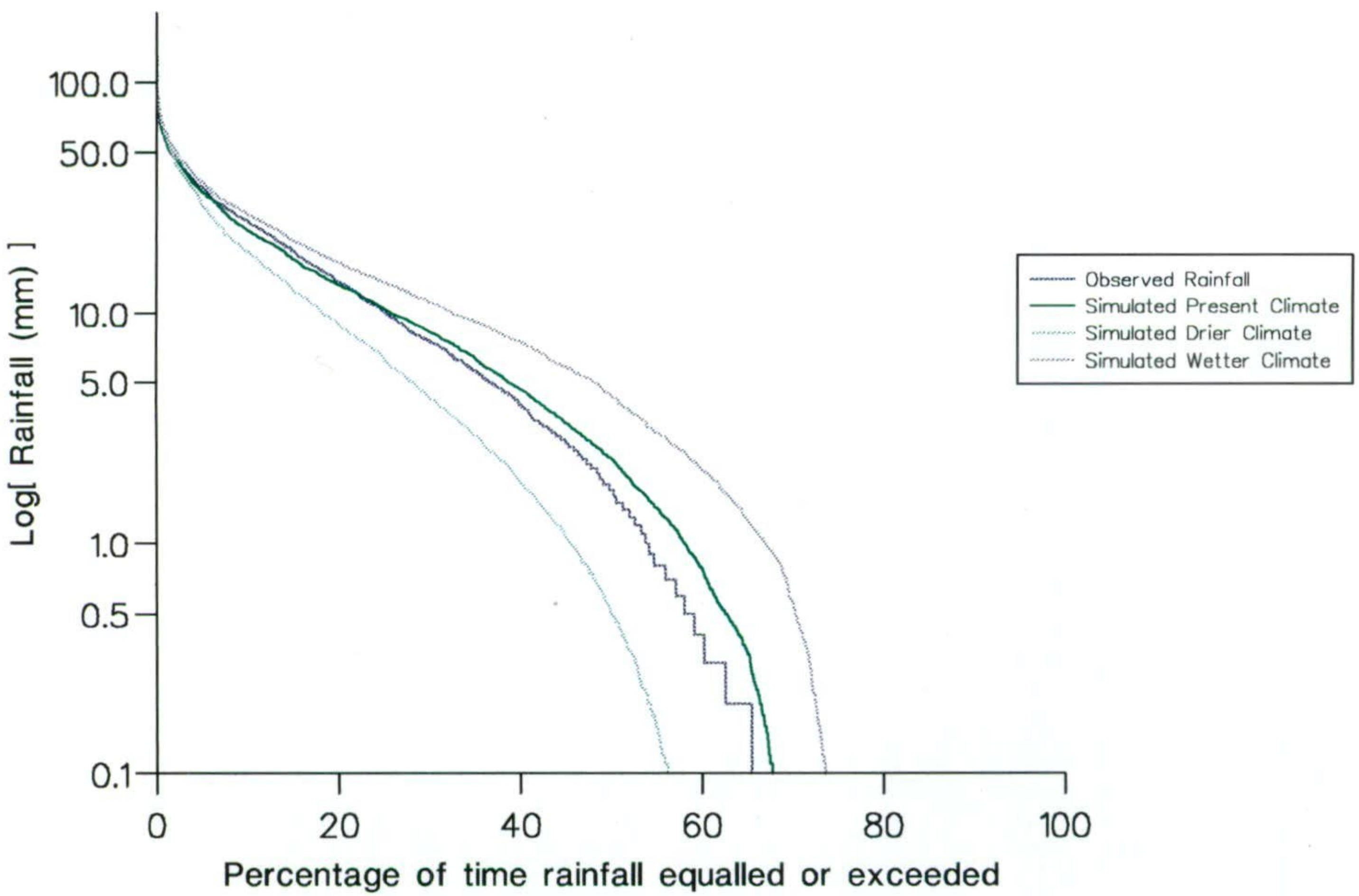


Figure 8

Table 3 Mean rainfall on a wet day and mean seasonal rainfall for simulated rainfall sequences.

Month	Present Climate		Drier Climate		Wetter Climate	
	Mean on Wet Days	Mean Total	Mean on Wet Days	Mean Total	Mean on Wet Days	Mean Total
Dec	16.41	938.0	14.03	753.0	17.16	1079.0
Jan	13.24		11.91		15.95	
Feb	10.46		8.78		11.45	
Mar	12.60	540.0	11.34	435.0	14.70	706.0
Apr	6.23		4.93		6.78	
May	7.59		6.25		9.47	
Jun	6.39	468.0	5.03	361.0	7.96	579.0
Jul	8.06		6.73		8.93	
Aug	10.69		10.56		11.97	
Sep	11.35	923.0	9.51	701.0	12.63	1137.0
Oct	14.41		12.71		16.38	
Nov	12.97		10.64		16.68	

4) Application of a semi-distributed hydrological model to future rainfall scenarios

4.1) TOPMODEL

The hydrological model selected to test the data was TOPMODEL [4,5,6], a physically based, semi distributed hydrological model which has been extensively used as a research tool for understanding rainfall-runoff processes in upland catchments [5,23]. It is introduced in this study for three reasons. Firstly, to assess whether synthetic rainfall series produced by the stochastic rainfall generator model produces realistic river flows. Secondly, to investigate the 'wetness', characterised by the depth to the water table, across the catchment under future climate scenarios. Thirdly, to investigate the potential for using TOPMODEL at a regional scale within the linked model framework.

A brief description of the theory behind TOPMODEL is given here. A more complete description can be found in other texts [4]. The version of the model used in this study relies on three basic assumptions. These are;

1. The downhill subsurface flow is composed of a linear addition of steady-state flows from hillslope segments.
2. These flows are described by the relationship,

$$q_i = T_o e^{z/} \tan\beta \qquad (4)$$

where q_i = is the local lateral flow per unit length of contour,
tanß is the local hydraulic gradient,
T_o is the lateral transmissivity when the soil is saturated to the surface,
f describes the exponential decrease in soil transmissivity with depth,
z_i is the local depth to the water table.

3. The local hydraulic gradient, tanß, is approximated by the local surface gradient.

It can be shown [4] that the local depth to the water table is given by;

$$z_i = \bar{z} + \lambda - \ln(a_i/\tan\beta)/f \qquad (5)$$

where $\bar{z}$ is the areal average depth to the water table,

a_i is the up slope area draining past a point per unit contour length and that;

$$\lambda = 1/A \int_0^A \ln(a_i/\tan\beta_i)\,di \qquad (6)$$

Where A is the total catchment area.

Essentially equation (6) implies that every point in the catchment with the same value of ln(a/tanß) will act in a hydrologically similar way. Thus, the distributed topographic information used by TOPMODEL is completely specified by the spatially aggregated distribution of ln(a/tanß) . In practice the model calculations are carried out at discrete intervals of ln(a/tanß) which makes the model semi-distributed. Given the mean depth to the water table $\bar{z}$, equation (6) can be used to predict the local depth to the water table at each time step. This feature of TOPMODEL is utilised in this study. In areas of the catchment where the water table is at the surface ($z_i <= 0$) the rainfall reaching the surface becomes overland flow. Substituting Equation (6) into Equation (5) and summing over the catchment gives the total subsurface flow;

$$q = T_o e^{-\bar{z}\cdot f - \lambda} \qquad (7)$$

The total stream flow is the sum of the overland flow from the saturated contributing area and the subsurface flow, q.

At each time step the value of $\bar{z}$ is updated for use in the next interval;

$$\bar{z}_{t+1} = \bar{z}_t + (q_t - qv_t)/\Delta\Theta \qquad \text{Equation (8)}$$

where; $\Delta\Theta$ is the storage capacity of the soil as a proportion of total soil volume,

qv_t is the total vertical flow through the unsaturated zone down to the saturated zone. qv_t is calculated by summing the local values of vertical drainage qv_{ti}. These are derived by assuming the hydraulic conductivity has an exponential profile with depth (with the same exponential decay parameter, f, as for lateral flow) and that near the water table there is unit hydraulic gradient. Local vertical flow is then given by

$$qv_{t_i} = K_0 e^{-zf} \qquad (9)$$

where K_0 is the vertical conductivity at the surface.

4.2) Topographic Index Distribution

The topographic heterogeneity of TOPMODEL is specified by the distribution of ln(a/tanß). This is calculated from a digital terrain map (DTM). The DTM described in Robson *et al.* [23] was used in this study. It's grid nodes are 100 m apart. The values of ln(a/tanß) were calculated for each grid square using a multidimensional routing approach described in Quinn *et al.* (1991) [21]. In this case the area, a, is the area of the catchment which drains through a grid square and tanß is the average surface slope within the grid square. A map of the index values for the Monachyle catchment is given in Figure 9. If ln(a/tanß) is large then either a is large (the area draining through a grid square is large) or tanß is small (the grid square is relatively flat). This would suggest that the greater the value of ln(a/tanß) for a grid square the more likely it is to be wet.

4.3) Calibration

TOPMODEL was calibrated using rainfall and flow records from the Monachyle catchment, Balquhidder, Scotland for the year June 1984 - June 1985. Three parameters were unknown and allowed to vary within realistic bounds. These were, f, the exponential decay rate in transmissivity, K_o the surface conductivity and, T_o the transmissivity at the saturated surface. Optimization was carried out using the Nelder-Mead Simplex procedure [18] to minimise the least square error between observed and simulated flows. The optimised parameters are f=12.6, K_o=80.6 and T_o=0.89. Figure 10 shows the rainfall and the simulated and observed flow. The model gives a satisfactory fit throughout the year (R^2=0.78). A validation of this model for the Monachyle was carried out on rainfall and flow data for the year June 1987 - June 1988. The model again gives a satisfactory fit throughout the year (R^2=0.64).

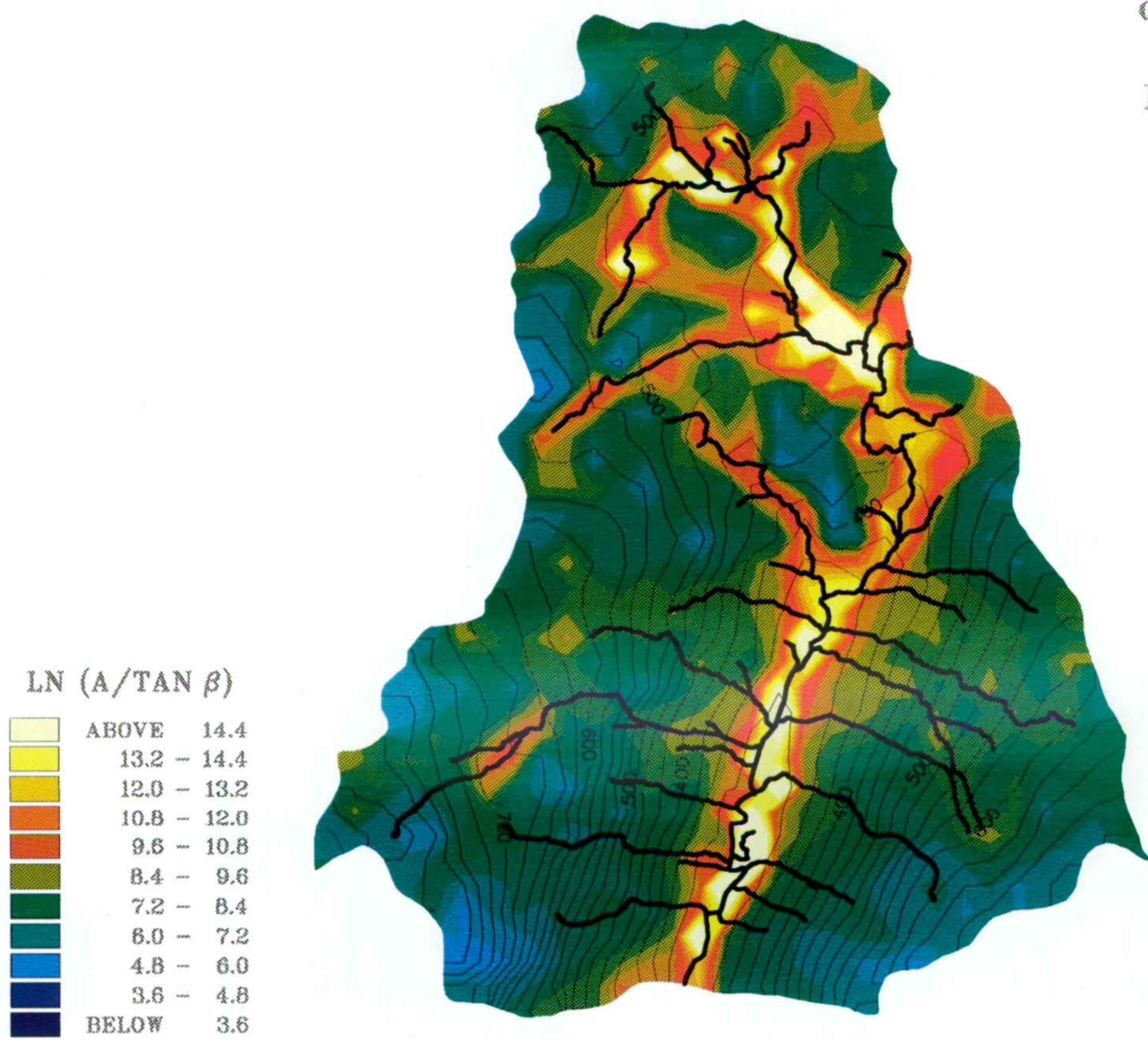
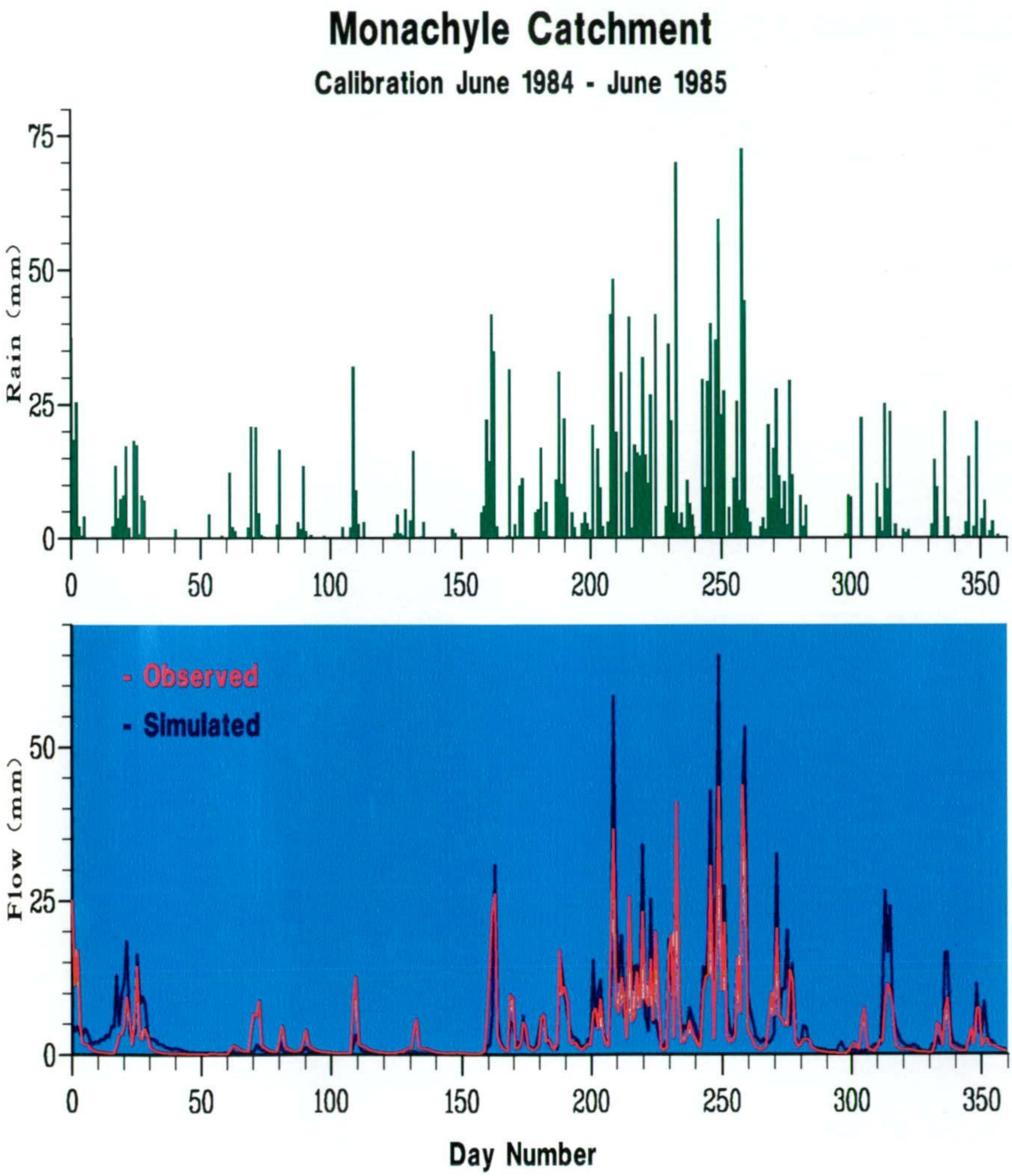

Monachyle catchment
Balquhidder
LN (A/TAN β)
ABOVE 14.4
13.2 – 14.4
12.0 – 13.2
10.8 – 12.0
9.6 – 10.8
8.4 – 9.6
7.2 – 8.4
6.0 – 7.2
4.8 – 6.0
3.6 – 4.8
BELOW 3.6
500
400
600
700

Figure 9

Figure 10


Monachyle Catchment
Calibration June 1984 - June 1985
Rain (mm)
0
25
50
75
0
50
100
150
200
250
300
350
- Observed
- Simulated
Flow (mm)
0
25
50
0
50
100
150
200
250
300
350
Day Number

4.4) Application of TOPMODEL

Having established that TOPMODEL can reproduce observed flows fairly accurately given an observed rainfall series it was applied to the catchment using synthetic rainfall generated by the two state Markov chain model. This was for the present climate and the two future scenarios previously described (Section 3.3). The effects of climate change are further compounded by changes in Potential Evapotranspiration (PE) . This is dependent on solar radiation, atmospheric moisture, wind and plant characteristics. All of these could be affected by a future climate change scenario. The error associated with any calculation of PE is increased by the possibility of change in the composition of vegetation across the catchment. The cumulative uncertainty involved in computing PE for a future scenario from first principles make it impractical. In this study two PE scenarios are used. Firstly there is no change in PE and secondly it increases by 4% for every degree rise in temperature. This relationship was suggested by Budyko [8] and first employed by Nemac and Shaake [19]. For this study the temperature was assumed to rise by 1°C in the summer and 2°C in the winter this results in a 4% increase in PE during the summer and a 8% increase during the winter using the second scenario.

TOPMODEL was applied to the Monachyle catchment with three combinations of synthetic rainfall and evapotranspiration scenarios. Firstly, rainfall for the present climate with no change in evapotranspiration in order to compare the models performance using synthetic and observed rainfall. Secondly, the synthetic dry climate rainfall with evapotranspiration increased as described above, intended to reflect an extreme dry climate. Thirdly the synthetic wet climate rainfall with no increase in evapotranspiration, intended to reflect an extreme wet climate.

The two state stochastic rainfall generation model has been proven to reproduce observed quantities of rainfall fairly accurately (Figure 8 and Table 2) but is limited in its ability to reproduce the observed persistence in rainfall events. The repercussions of this limitation are highlighted when the distribution of simulated flow produced by TOPMODEL using simulated rainfall is compared to that of observed flows. Figure 11 shows flow duration curves for simulated and observed flows. There is no increase in evapotranspiration in the wet and dry climate scenarios. For approximately 20% of the time the flow exceeds approximately 6.5 mm for the observed flows and the simulated flow using simulated rainfall for the present climate.The model run on simulated rainfall overestimates the percentage of time flows below this are exceeded and underestimates the percentage of time flows above this are exceeded. This is related to the lack of persistence exhibited by the synthetic rainfall. A rainfall series with persistent periods of rain will produce a greater number of high flows than one in which the rain events are more evenly spread through time. The percentage time flows are exceeded was greater in the future wet scenario and smaller in the future wet scenario, as would be expected. The difference between the percentage exceedance of flow curves produced from observed and modelled rainfall for the present climate is sufficient to conclude that synthetic rainfall generated from the two state markov chain model produces unrealistic river flows.

4.5) Saturation of the Catchment as Predicted by TOPMODEL

An integral part of TOPMODEL is that it keeps track of the depth to the water table for discrete classes of $\ln(a/\tan\beta)$. So, if $\ln(a/\tan\beta)$ is known for a grid square, TOPMODEL can

Simulated Flow

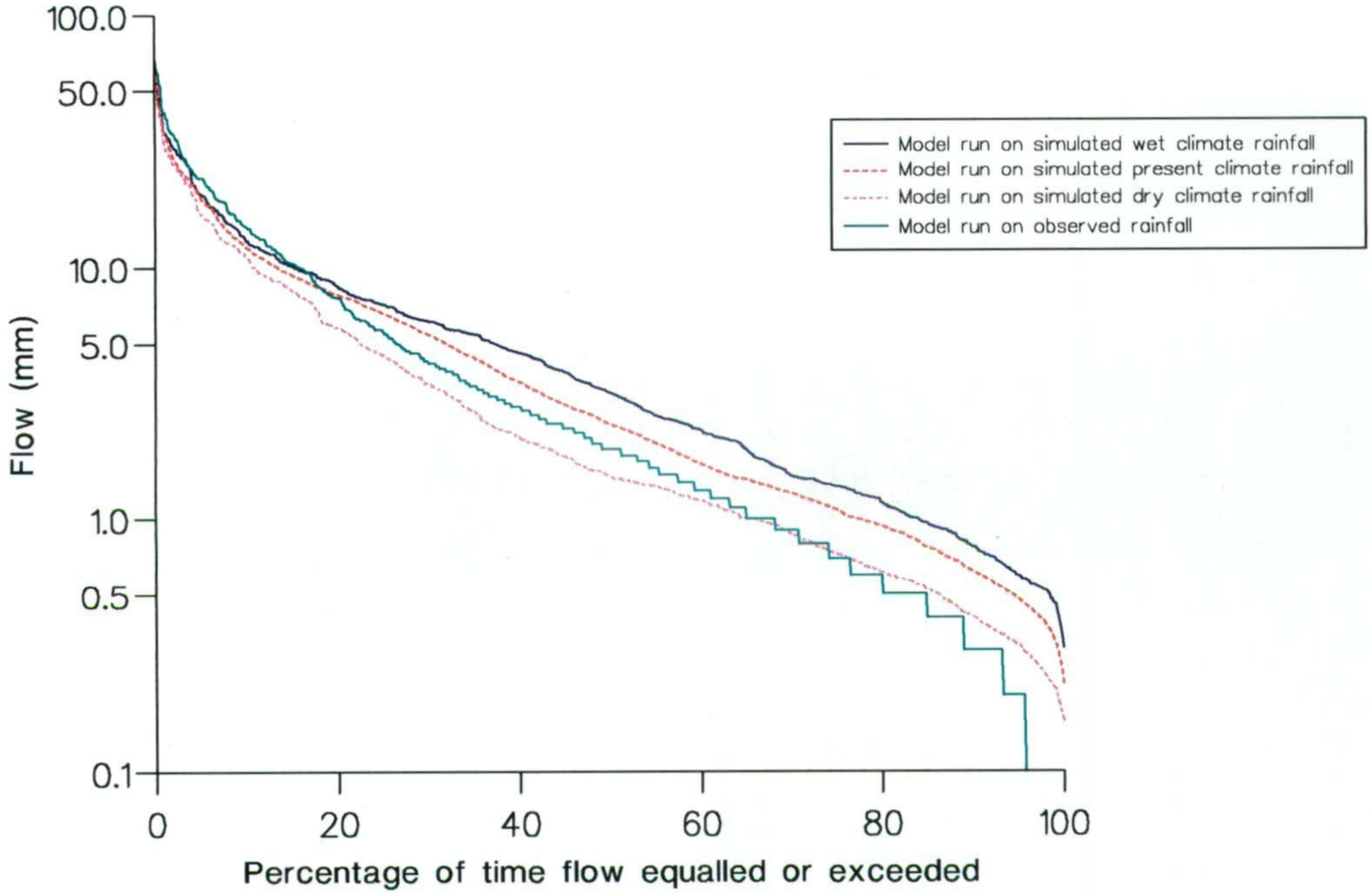


Figure 11

Monachyle Catchment (Balquidder)

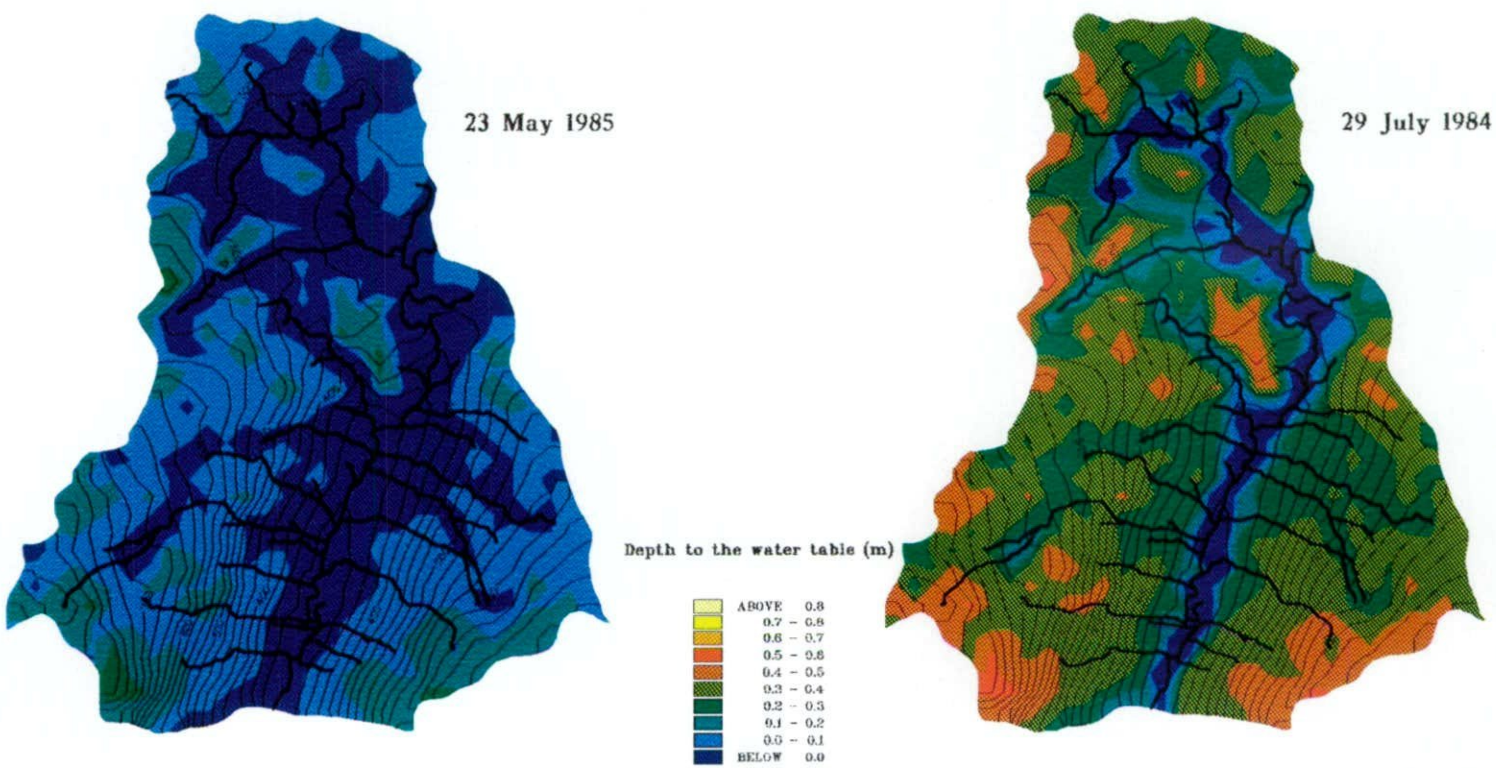


Figure 12

predict the depth to water table. This is demonstrated by the two maps of the simulated depths to the water table displayed in Figure 12. These are for 29th July 1984, which was at the end of a sustained dry period, and 23rd May 1985, which was during a storm. On the 29th July only a small portion of the catchment around the stream is saturated to the surface, the mean depth was 0.28 m and the maximum depths was 0.6 m . On 23rd May a much larger portion of the catchment is saturated to the surface. Rain falling on this saturated area will flow quickly to the stream. The mean depth to water table across the catchment was 0.03 m and the maximum depth was 0.4 m. This feature is used here to investigate the use of TOPMODEL in predicting how the wetness of the catchment might change under future climate scenarios. Unfortunately, few soil moisture or piezometer data exist to test the validity of this prediction. Given that this measure of catchment wetness might be important in determining vegetation species distribution [15] and that validation data could be collected in the future if desired, the analysis was continued. The two state markov chain model was used to generate rainfall series for the future wet and dry climates previously described, its limitations were ignored.

It was anticipated that large areas of the catchment would saturate more frequently under future wetter climate and less frequently under a drier climate. To test this hypothesis, maps of the percentage of time TOPMODEL simulated saturation to the surface for each grid square were constructed for the three climate scenarios previously described; for the model run using simulated present climate rainfall, using simulated future wet climate rainfall with no increase in evapotranspiration, and using simulated future dry climate rainfall with an increase in evapotranspiration. The second and third maps are for the most extreme wet and dry climates considered.

Little difference is apparent in these maps (Figure 13). Parts of the catchment close to the stream tend to remain saturated to the surface 90 to 100% of the time for all three scenarios. Areas of the catchment above approximately 500 m tend to be saturated to the surface less than 10% of the time for all the scenarios. Changes in the frequency of saturation for different climates would appear to be limited to a relatively small region between these two zones. The topographic index ($\ln(a/\tan\beta)$) tends to lie between 8 and 11. Histograms of the frequency with which depths to the water table occurred for areas of the catchment in which $\ln(a/\tan\beta)$ lies between 8.4 and 10.8 are shown in Figure 14 $\ln(a/\tan\beta)$.

On the evidence of these maps and histograms the hypothesis that large areas of the catchment would saturate more frequently under a future wetter climate and less frequently under a drier climate is not supported for the Monachyle catchment. This is reasonable for the lower part of the catchment since the valley bottom is flat and remains saturated 90% of the time, even under present climate conditions. Conversely, the valley walls are too steep to remain consistently saturated. In the upper part of the catchment the valley floor is relatively flat and, under present climate conditions, the area saturated a high percentage of the time is restricted to a band close to the stream. It was expected that this band would expand significantly under a wetter climate and contract under a drier climate. The failure of the hypothesis here could be attributed to some inadequacy in the model, however, it is more likely due to limitations of the stochastic rainfall generator. Its ability to simulate the observed persistence in rain events is poor. Hence, although the quantity of rainfall changes significantly between climate scenarios, its duration does not. As a result, TOPMODEL predicts significant changes in surface runoff from the saturated contributing area without

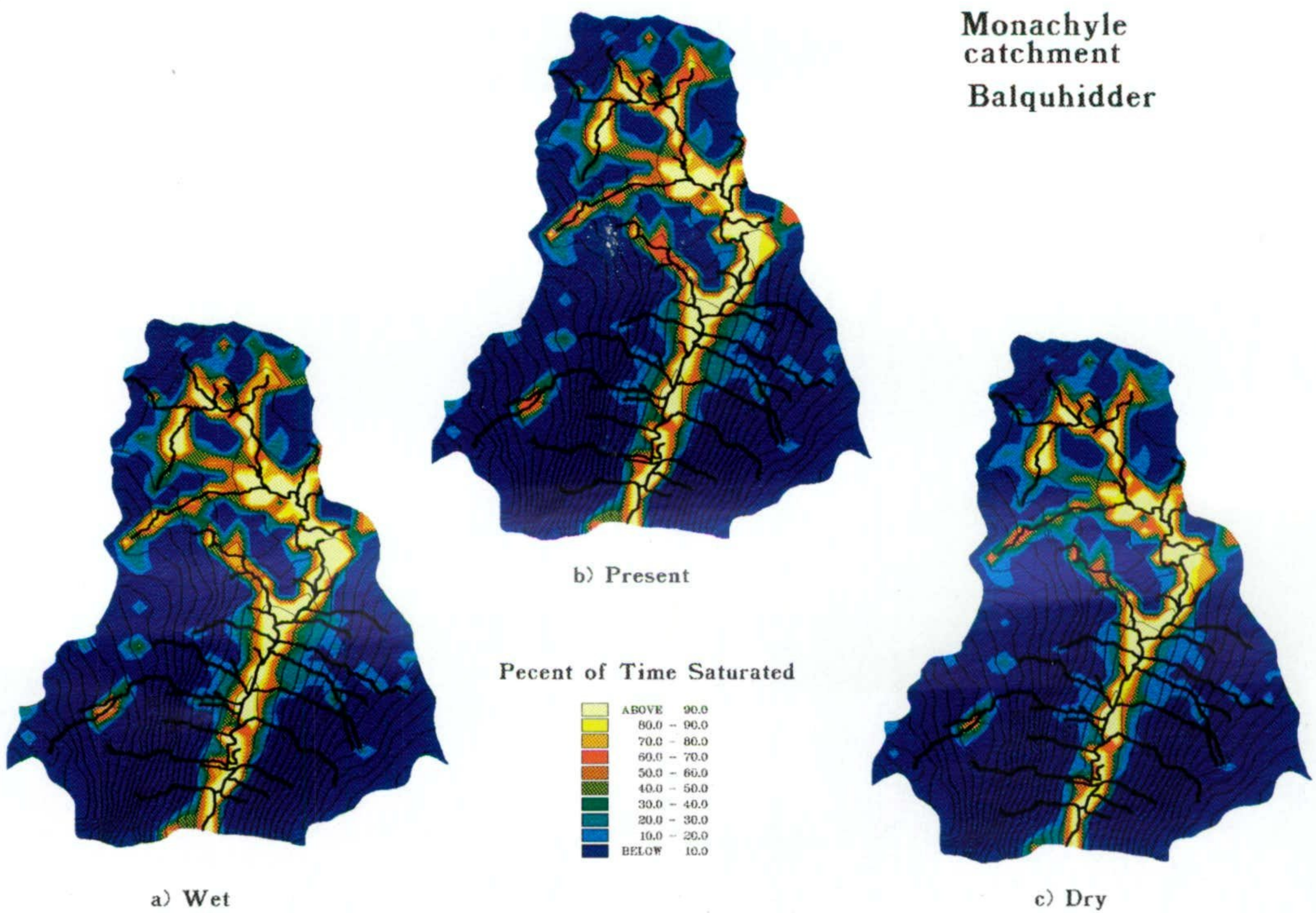

Monachyle
catchment
Balquhidder
b) Present
Pecent of Time Saturated
ABOVE 90.0
80.0 - 90.0
70.0 - 80.0
60.0 - 70.0
50.0 - 60.0
40.0 - 50.0
30.0 - 40.0
20.0 - 30.0
10.0 - 20.0
BELOW 10.0
a) Wet
c) Dry

Figure 13

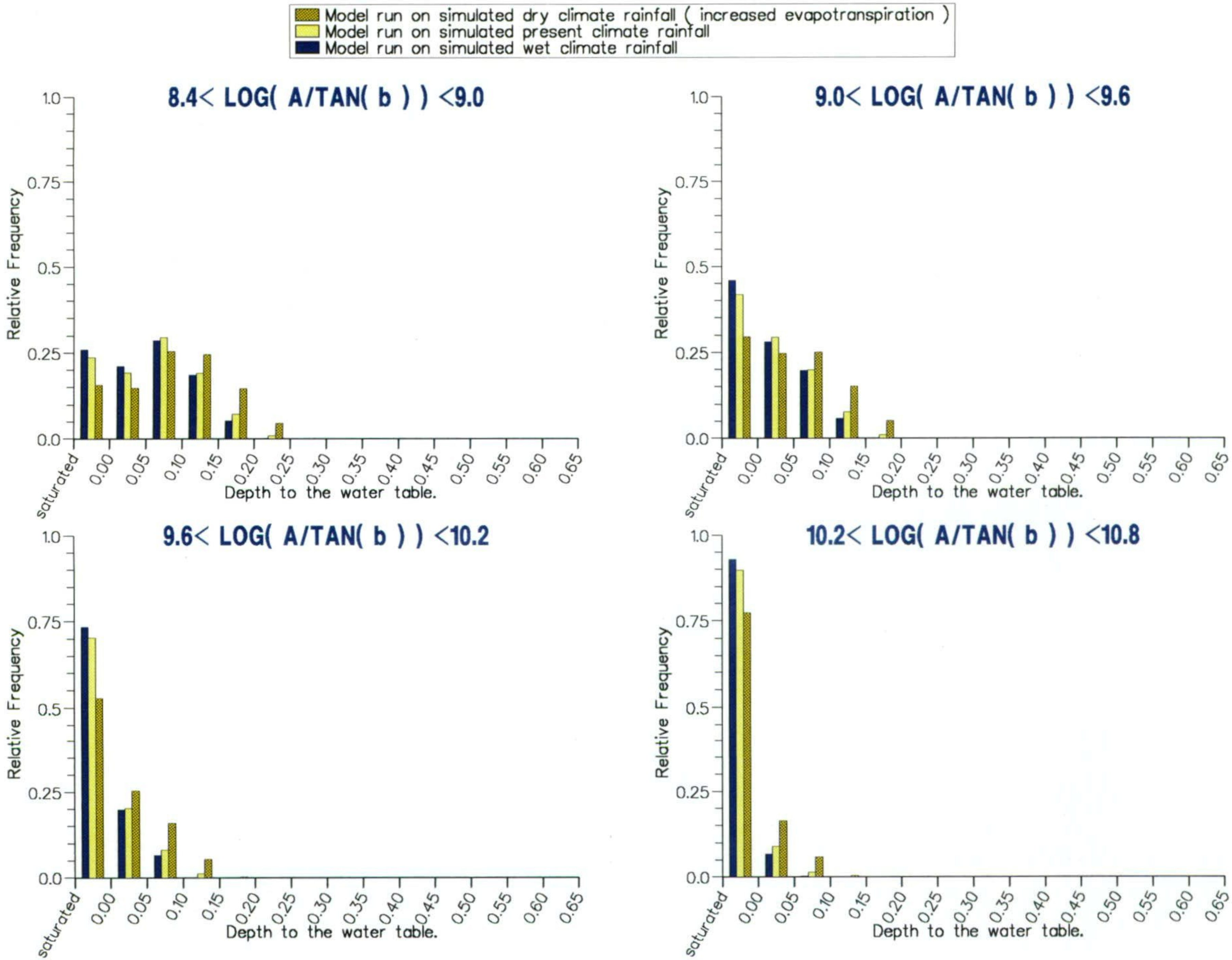

Model run on simulated dry climate rainfall (increased evapotranspiration)
Model run on simulated present climate rainfall
Model run on simulated wet climate rainfall
8.4< LOG(A/TAN(b)) <9.0
9.0< LOG(A/TAN(b)) <9.6
9.6< LOG(A/TAN(b)) <10.2
10.2< LOG(A/TAN(b)) <10.8
Relative Frequency
1.0
0.75
0.5
0.25
0.0
saturated
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
0.65
Depth to the water table.

Figure 14

changing the length of time these areas are saturated.

5) Regional use of a semi-distributed hydrological model

The hydrology of a catchment is influenced by topography, land use, soil type and climate. The relative importance of these varies significantly within the U.K. However, it is possible to define regions within which the hydrological responses of the catchments are dominated by similar characteristics. Upland Scotland and the flat lands between the Thames and the Wash are two such regions. A model capable of simulating the hydrological response of one catchment in the region is likely to be applicable at all the others. Here, the use of TOPMODEL as the core hydrological model within the overall linked model, for upland regions is discussed.

In the context of this project there are three criterion on which a potential hydrological core model should be judged;

1) the ability of the model to simulate the observed hydrologic response of the catchments in the region,
2) the model inputs should be readily available on the GIS,
3) it should be possible to automate the link between the GIS and the model.

TOPMODEL certainly fulfils the first of these as it has been applied successfully at numerous upland catchments [5,23].

Inherent in the structure of TOPMODEL is the assumption that the hydrological response of upland catchments in humid temperate climates are dominated by subsurface runoff and by surface runoff from areas of saturation that expand and contract through the storm period, termed variable source areas. The relative importance of these is determined by the hydraulic properties of the soil and by catchment topography. This information is characterised by the soil hydraulic conductivity, the local slope ($\tan\beta$) and the area drained per unit contour (a). The soil hydraulic conductivity for UK catchments can be estimated from the data sets underlying the HOST data set on the GIS. The critical topographic information for a catchment as a whole is the spatially aggregated distribution of $\ln(a/\tan\beta)$. This is calculated from a digital terrain map using a multidimensional routing algorithm [21] which requires no user interface. The GIS contains a DTM and so in theory criterion 3 is satisfied. However, the DTM is on a 1 km^2 grid and Quinn *et al.* [21] suggest that for the routing algorithm to produce effective distributions of $\ln(a/\tan\beta)$, the grid size should reflect those features which are vital to the hydrologic response. Many upland catchments (*e.g.* Monachyle) cover less than 10 km^2 hence our grid is too large for upland catchments and criterion 2 is not satisfied. Experimentation with the grid size of the DTM for the Monachyle catchment suggests that the $\ln(a/\tan\beta)$ distribution changes significantly with grid size (Figure 15), however, this has little effect on the predicted runoff until the grid size exceeds 100 m by 100 m. Generally, the larger the grid size, the lower the percentage of low $\ln(a/\tan\beta)$ values. This is partly due to the fact that very low values of $\ln(a/\tan\beta)$ can no longer exist due to the large increase in

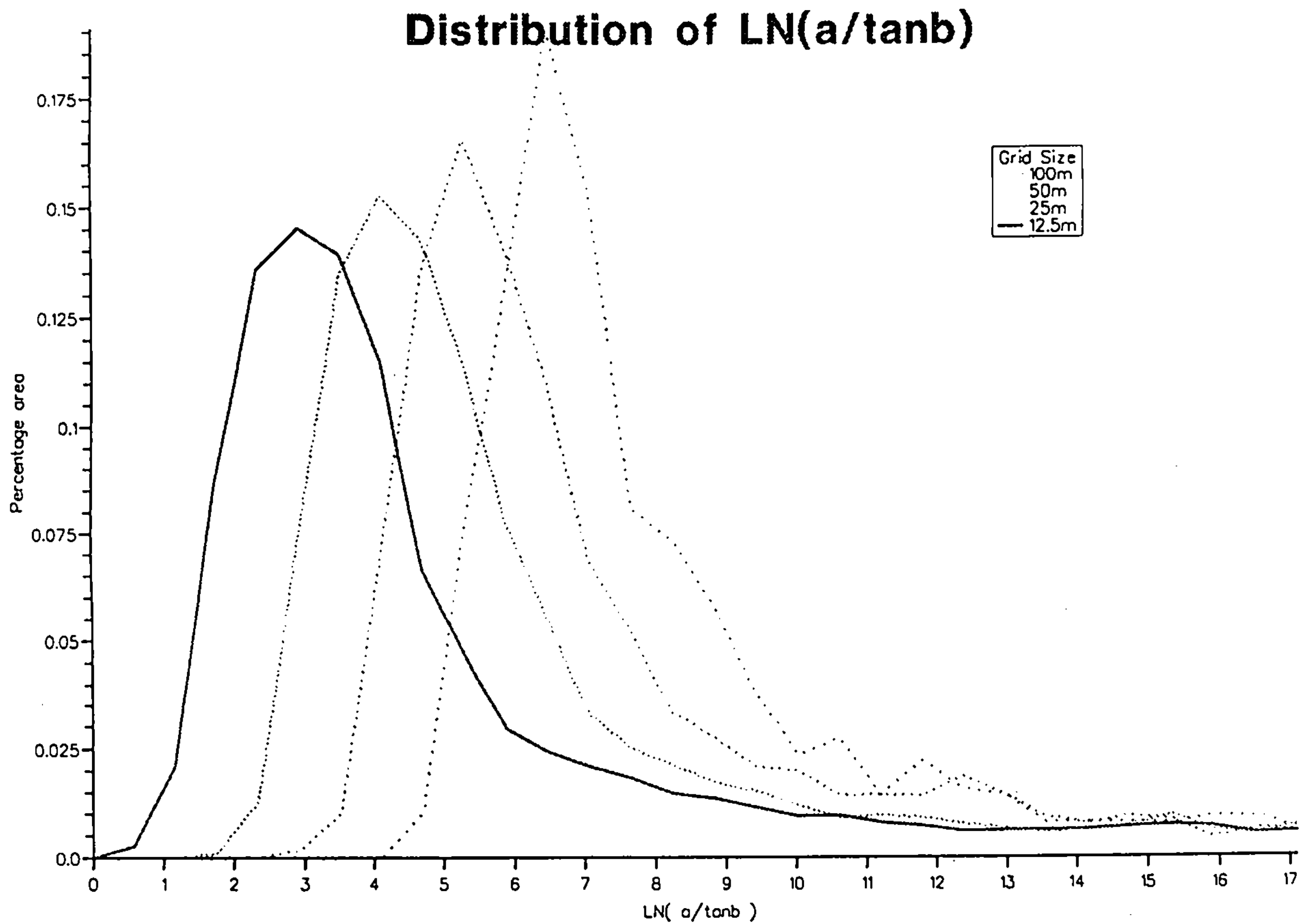


Figure 15 Distribution of ln(a/tanß).

area of each grid square.

In summary, TOPMODEL would be suitable as a core hydrological model for upland regions if the GIS contained a DTM on a grid scale of 100 m by 100 m or less. At present, however, the DTM is on a grid of 1 km^2 and this precludes the use of TOPMODEL within the framework of the linked model. The Institute of Hydrology are currently in the process of constructing a 50 m by 50 m DTM which, when complete might enable TOPMODEL to be included as the core hydrological model for upland regions. This is not, however, likely within the time frame of the current research programme.

6) The vegetation model

The work described here concentrates on the ecological component of the research to predict, in response to scenarios of environmental change, the dynamics of vegetation within a catchment and the way in which these dynamics influence biogeochemical processes.

6.1) The grassland model

A grassland model [26] is being developed (Figure 16) and this will be utilized as the main vegetation model within the framework of the linked model. Clearly grassland represents only one vegetation type within the UK and only dominates in the uncultivated upland areas. The development of further vegetation models will be considered in the future. The model is driven by light and temperature and requires water and nitrate inputs from the soil. Assimilate production is calculated from rates of photosynthesis and respiration. The influence of changes in CO_2 concentration are incorporated. The assimilate is then partitioned into leaves, stems and roots, new growth rates are calculated and the leaves, stems and roots are expanded accordingly. Routines for canopy expansion include new leaf growth, ageing and death of leaves. An optional harvesting routine (CUT) is also included.

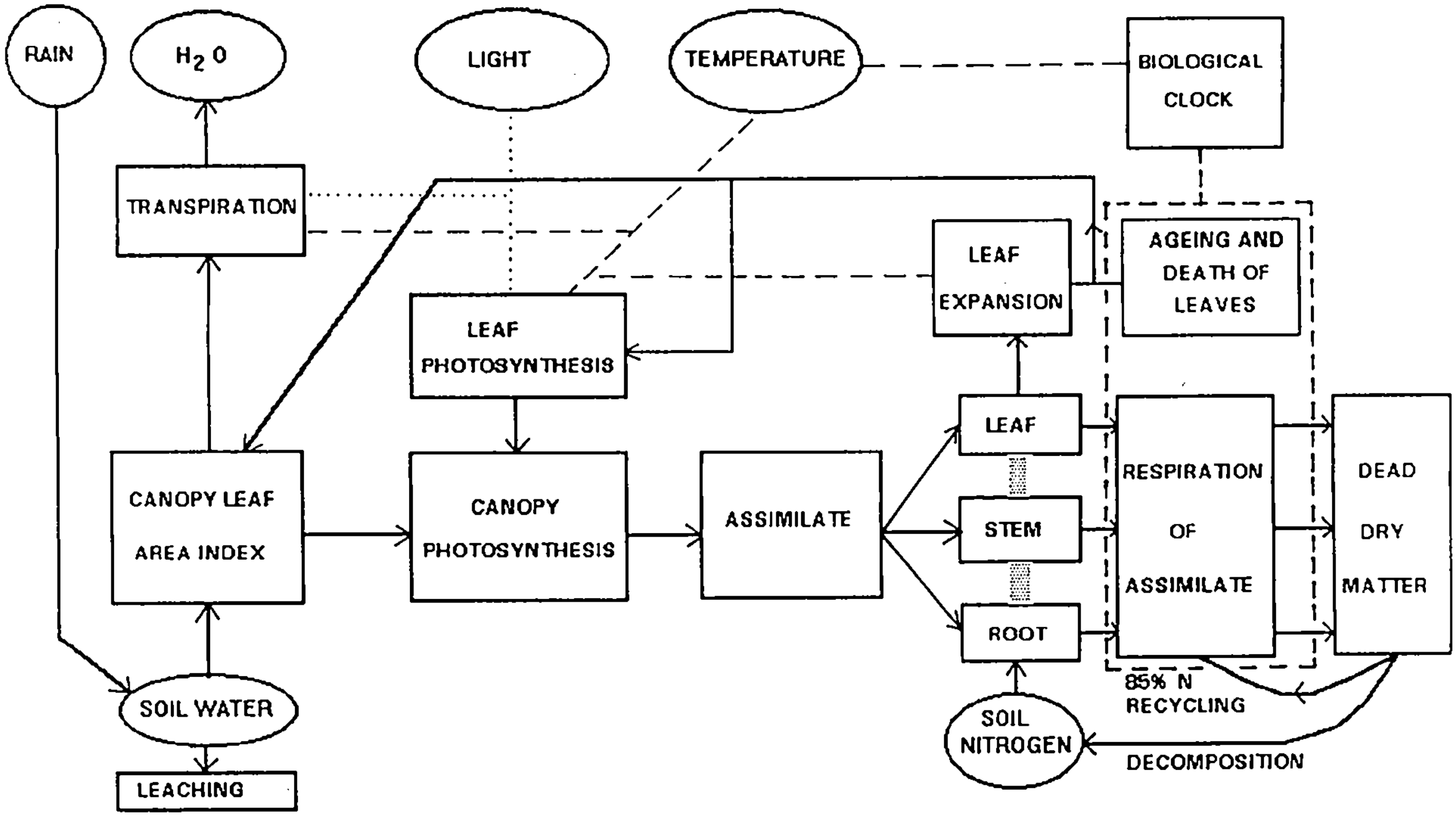
6.2) The Structure of the model

The model can be divided into seven steps;

(1) Generation of assimilate (photosynthesis).
(2) Partitioning of assimilate.
(3) Canopy expansion (leaf area).
(4) Respiration of assimilate.
(5) Ageing and death of tissue.
(6) Soil moisture and plant water loss (transpiration).
(7) Soil nitrogen uptake and recycling.

Each step is considered in terms of light and temperature in the following sections.

Figure 16 The grassland model.



6.2.1) The generation of assimilate

The calculations for the generation of assimilate by canopy 'gross' photosynthesis have been described in detail by Sheehy, Cobby and Ryle [26]. The response of canopy photosynthesis Pd(t) ($gCH_2O\ m^{-2}\ d^{-1}$) to irradiance I(t) ($J\ m^{-2}\ d^{-1}$) can be described by a hyperbolic equation;

$$Pd(t) = I(t)/AI(t) + B \qquad (10)$$

where 1/A is the maximum value of Pd(t) as irradiance tends to infinity and 1/B is the photosynthetic quantum efficiency of the canopy in low irradiance. Assuming that the level of daily irradiance varies sinusoidally during a daytime of length h the irradiance (I) at time t is described by;

$$I(t) = \frac{\Pi Sd}{2h} \sin \frac{\Pi t}{h} \qquad (0 \leq t \leq h) \qquad (11)$$

where Sd is the total amount of radiation observed on day d ($J\ m^{-2}$) and h(<1) and t (<1) are measured in days.

Substituting Equation (11) into Equation (10) and integrating over time the total weight of carbohydrate generated during day d is;

$$Pd = \int_0^h \frac{\pi Sf\sin(\pi/h)}{\pi SdA\sin(\pi/h) + 2hB} \qquad (g\ CH_2O\ m^{-2}) \qquad (12)$$

In the model the parameters A and B in Equation (12) are calculated from individual leaf and canopy characteristics. If 1/a is the maximum value of individual leaf photosynthesis (Pmax), 1/b is the quantum efficiency of an individual leaf in a canopy and f is the fractional light interception of a canopy with leaf area index L then;

$$A = a/(L+0.5) \qquad (13)$$

and

$$B = b/f. \qquad (14)$$

In Equation (13), the value of L was increased by 0.5 to allow for the photosynthetically active area of the sheath [27]. The fractional light interception $f=(1-e^{-kL})$ where k, the extinction coefficient for light, was taken to be 0.6, a value appropriate for grasses.

A linear relationship is used to describe the maximum rate of individual leaf photosynthesis at saturating irradiance (Pmax; $gCH_2O\ m^{-2}\ d^{-1}$) as a function of the average irradiance level [$I_0\exp(-kL)$] experienced by a piece of leaf on the day of its emergence, where I_0 is the irradiance incident at the top of the canopy. Thus

$$Pmax = m + nI_0\exp(-kL) \qquad (15)$$

where m is a temperature dependent parameter described by Equation (16) and n($gCH_2O\ J^{-1}$)

is a constant relating maximum photosynthetic rate to irradiance.

According to Sheehy *et al.* [26] it can be assumed that the optimum temperature for leaf photosynthesis in U.K. climates is 22°C and that at temperatures less than 5°C the rate of change of photosynthesis with temperature is relatively slow and the temperature dependent parameter can be written as;

$$m = cT^2 \exp(-T/q) \tag{16}$$

where c is a constant relating the value of m to temperature (c=0.025 $gCH_2O\ m^{-2}\ d^{-1}\ T^{-2}$), T is the average daily temperature (°C) experienced by a leaf on emergence and q is a constant such that the optimum temperature of photosynthesis is 2q (*i.e.* q=11 when T_{OPT} = 22°C). Thus the photosynthetic capacity of a leaf in relation to its growth is;

$$Pmax = cT^2 \exp(-T/q) + nI_0\exp(-kL) \tag{17}$$

The model includes a routine to allow for the effects of variable atmospheric CO_2 concentrations (Ca; $gCO_2\ m^{-3}$) on photosynthesis. The response of individual leaf photosynthesis to light can be simulated by a non-rectangular hyperbola with initial slope n (see Equation (17)) and asymptote Pmax. According to Thornley, Fowler and Cannell [29] the CO_2 dependence of n can be described by as;

$$n = n_m(1-\beta/g_cCa) \tag{18}$$

where n_m (the maximum value of n when Ca tends to infinity) = $1.0*10^{-5}$ $gCH_2O\ J^{-1}$, ß (a photorespiration parameter) = $0.3*10^{-3}$ $gCO_2\ m^{-2}\ s^{-1}$ and g_c (a CO_2 conductance) = 0.0015 $m\ s^{-1}$. Using Equation (18), the values of n at atmospheric CO_2 levels of 350 ppm (Ca=0.64 $gCO_2\ m^{-3}$) and 700 ppm (Ca=1.28 $gCO_2\ m^{-3}$) are $6.87*10^{-6}$ and $8.44*10^{-6}$ $gCH_2O\ J^{-1}$, respectively.

The dependence of Pmax on CO_2 concentration is modelled indirectly by relating maximum canopy photosynthesis (1/A in Equation (13)) to atmospheric levels of CO_2 (ppm) using an analogue of Ohm's law. At a nominal ambient CO_2 level of $[CO_2]$=350 ppm a simple canopy resistance to gaseous diffusion of CO_2 across the leaf surface [r_c; $ppm(gCH_2O\ m^{-2}\ d^{-1})^{-1}$] is calculated thus;

$$r_c = [CO_2]A \tag{19}$$

This diffusive resistance to CO_2 transfer in the canopy is then used to calculate the maximum rate of photosynthesis at elevated atmospheric CO_2 levels $[CO_2]'$ as described by;

$$A = r_c/[CO_2]' \qquad ([CO_2]'<350\ ppm) \tag{20}$$

6.2.2) Partitioning of assimilate

A simple relationship between photosynthesis and partitioning of assimilate was used in the model. Environmental and physiological factors exerted their influences on partitioning of assimilates through their effects on canopy photosynthesis.

The proportion of daily canopy photosynthate translocated to the roots (R) was assumed to be directly proportional to photosynthesis [28]. In order to take account of the delay in the change of the pattern of assimilate partitioning following a change in environmental conditions the average of daily canopy photosynthesis for the most recent three days is used. The relationship is shown in Figure 17 and is described thus;

$$R = k_R Pd \tag{21}$$

where k_R is the constant of proportionality, which is itself a function of nutrient levels and water stress, and Pd is the mean of 3 days photosynthesis.

The proportion of daily photosynthesis allocated to leaves (L) is assumed to decline linearly with Pd so a greater percentage was invested for leaf growth when Pd was small than when it was large. The relationship is;

$$L = 100\text{-}k_L Pd \tag{22}$$

where k_L is the constant of proportionality for leaves and is a function of nutrient levels and water stress. Consequently, the proportion of a day's assimilate distributed to the stem (S) can be assumed to be proportional to Pd thus;

$$S = k_S Pd \tag{23}$$

where k_S is the constant of proportionality such that $k_S=k_L-k_R$.

This simple model is consistent with the Brouwer hypothesis [7] which states that during early growth or following defoliation the partitioning of assimilates to leaf meristems will be a priority, in order to establish the photosynthetic capacity of the crop. As the capacity is restored there is a gradual increase in the partitioning to stems and roots until some form of equitable distribution is reached.

6.2.3) Canopy expansion

The model caters for a maximum of up to 5 live leaves per tiller in a sward and assumes there are 10,000 tillers per m^2 ground. For each leaf (1 -5) a day's newly emerged leaf area is put into a one dimensional array of 40 elements, allowing for a leaf longevity of up to 40 days. When the oldest leaf (≤leaf 5) on a tiller dies, as determined by the 'biological clock' (see Section 6.2.5), its leaf area is discarded and the values in the elements of each of the existing leaf arrays are transferred up to the next leaf array (*i.e.* leaf 4 becomes leaf 5, leaf 3 becomes leaf 4 *etc.*) and the values of the elements for leaf 1 are set to zero.

A day's newly emerged leaf area is calculated on the basis of a potential rate of leaf expansion (RLE; $m^2\ m^{-2}$ ground d^{-1}) defined thus;

$$RLE = R_{TE}\ Td\ w\ N_T \tag{24}$$

where R_{TE} is the thermal rate of leaf extension [$R_{TE}=7.5*10^{-4}$ m d^{-1} $(^{\circ}C)^{-1}$], Td is the daily mean temperature, w is leaf width ($w=5.0*10^{-3}$ m) and N_T is the number of tillers per

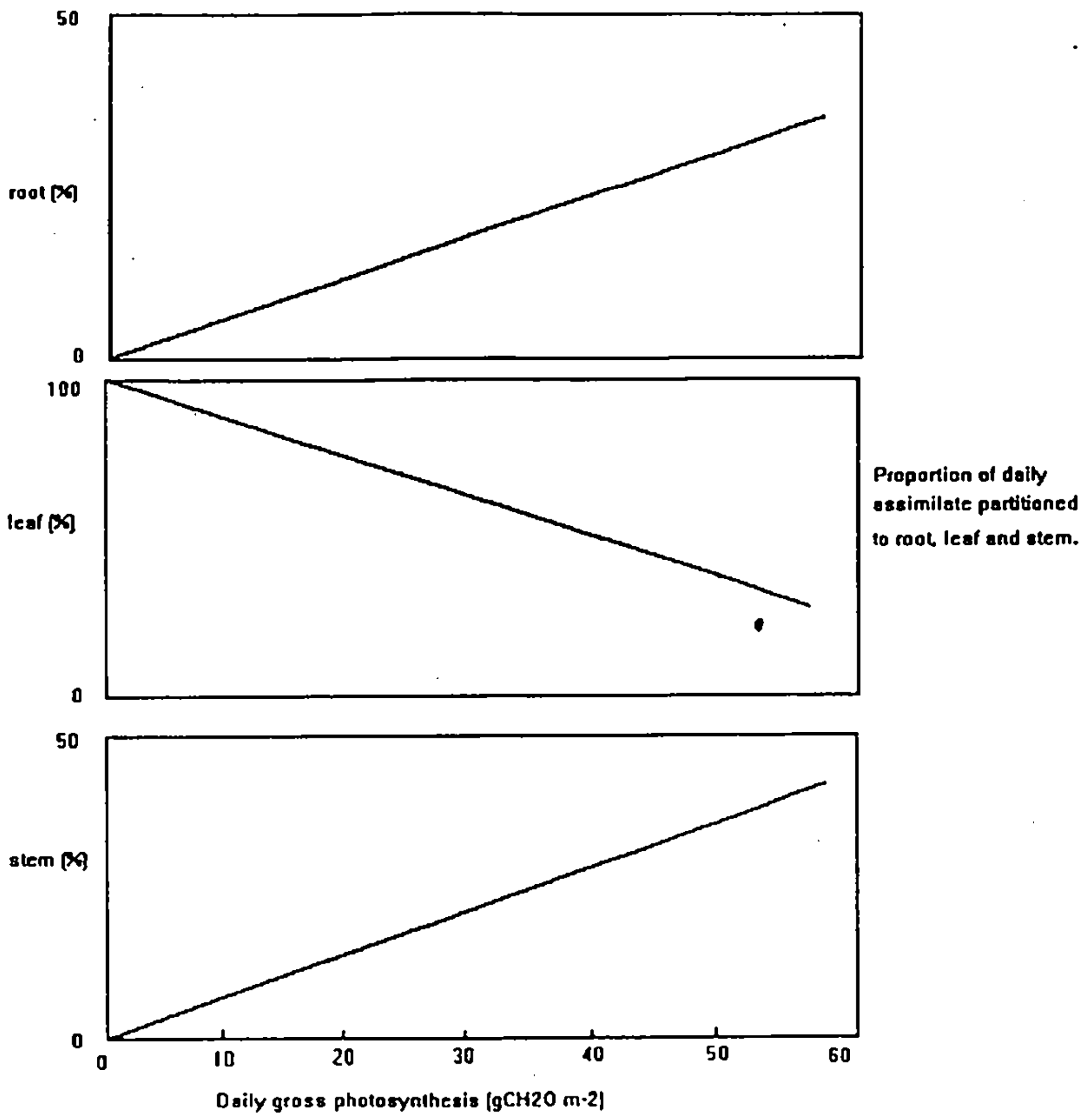


Figure 17 The relationship between the percentage of assimilate distributed to root, leaf and stem as a function of daily canopy photosynthesis.

m^2 ground (=10,000). This potential rate of leaf expansion is limited by both assimilate supply and soil moisture in the model.

The daily transformation of assimilate into unexpanded leaf area in the leaf sheath (A_{ul}; m^2 m^{-2} ground d^{-1}) is described by;

$$A_{ul} = W_l.SLA \tag{25}$$

where W_l ($gCH_2O\ m^{-2}\ d^{-1}$) is the amount of assimilate partitioned to leaf growth each day and SLA is the specific leaf area ($m^2\ g^{-1}$) calculated from;

$$SLA = (a\mathrm{Td} + b)\exp[-cI_o\exp(-kL)] \tag{26}$$

In Equation (26), a (=1.2 $m^2\ g^{-1}\ T^{-1}$), b (=46 $m^2\ g^{-1}$) and c (=0.029*10^{-6} $J^{-1}\ m^2$ day) are constants, I_o is the irradiance incident on the canopy and the function *exp(-kL)* describes the irradiance level experienced by the developing leaf in the sward.

On a given day, if the value of A_{ul} is less than RLE then RLE becomes A_{ul}. The effect of water stress on leaf expansion is modelled on the basis that soil water potentials (ϕ) greater than 0.1 MPa cause an exponential decline in RLE thus;

$$RLEw = RLE.\exp(-3.4(\phi-0.1)) \tag{27}$$

where RLEw is the water stressed rate of expansion. From Equation (27) it can be seen that RLEw is practically zero at ϕ>1.0 Mpa, a value consistent with soil water potentials at the permanent wilting point [12]. The exponential decline in RLE with increasing soil water potential reflects the characteristics of the soil moisture release curve of available soil water against soil water potential.

6.2.4) Respiration of assimilate

The method of describing respiratory loss of assimilate in the model is described in terms of two main components. The first component is a fast exponential decay of fixed carbon lasting approximately 24 h associated with the biosynthesis of new tissue and generally known as growth respiration. Growth respiration is generally found to be insensitive to light and temperature and accounts for the loss of about 25% of carbon fixed at any instant. The second component of respiration can be characterized by a slow exponential decay amounting to 1 to 2% of the carbon remaining at any time after fixation and is associated with the maintenance of metabolic activity. The rate of this so called maintenance respiration is temperature dependent and in the model a Q_{10} of 1.5 is used giving rates of 1%, 1.5% and 2.25% per day at temperatures of 5, 15 and 25°C, respectively.

The general function used to describe the total weight of assimilate remaining after respiration on day d (Wd; $gCH_2O\ m^{-2}$) is;

$$Wd = \Sigma^{d}_{i=1}(f_i P_{d+1-i})/h \tag{28}$$

where Pd is the total assimilate produced during day d throughout a day length period of length h and f_i is the proportion of a day's assimilate unrespired i days after its formation.

So, when i=1;

$$f_i = \frac{(1-g)/h^{-1}}{\ln(1-g)}(1-(1-g)^{-1} \tag{29}$$

where g is the rate of growth respiration (g=0.25), and when i=2,3....d;

$$f_i = \frac{(1-g)(1-m)^{i-1}}{\ln(1-m)} h^{-1}(1-(1-m)^{-h}) \tag{30}$$

where m is the rate of maintenance respiration, typically m= 0.015 at 15°C. Equation (28) simply states that the weight of assimilate in the sward at the end of day d is made up of the sum of fractions of assimilate formed during previous days less the fractional respiratory losses.

6.2.5) Ageing and death of tissue

In a vegetative grass crop the production of a new leaf is generally balanced by the death of an old leaf and there are approximately three live leaves per tiller [10]. This assumption of the orderly death of leaves is used in the present model. Rates of leaf appearance and senescence were assumed to be a function of temperature. The 'biological' clock routine used in the model assumes there is an exponential decline in carbon compounds via growth and maintenance respiration (see previous Section). When the fractional loss is 0.35 a new leaf appears and the clock resets to 1.0 and starts running down again until it reaches 0.65. The clock is temperature sensitive because maintenance respiration is temperature sensitive. This clock is based on the observations of Peacock [20] and gives leaf appearance rates of 22, 10 and 6 days per leaf at temperatures of 5, 15 and 25°C, and thus the life spans of the leaves are 66, 30 and 18 days.

The rate of senescence is based on the assumption that a piece of leaf dies when it has lost 50% of its initial weight through respiration (*i.e.* in Equation (30) the term f_i=0.5). From calculations based on the respiration model the approximate life spans of leaves using this method are 40, 27 and 18 days at temperatures of 5, 15 and 25°C; the largest discrepancy between these values and those generated by the 'clock' routine occurs at 5°C, a temperature at which growth is extremely slow and one at which the discrepancy would have only a small effect. The same assumption is used to 'kill' stem but roots are considered to survive until 90% of their initial weight is lost through respiration.

The pattern of decline of leaf photosynthesis with age in a grass crop, as reported by Marks and Taylor [17] and Woledge [33] is idealized as shown in Figure 18 and described by;

$$\mathrm{Pmax(d)} = \mathrm{Pmax(i)}/(1+\exp(0.44(\mathrm{d}-\mathrm{D}/2))) \tag{31}$$

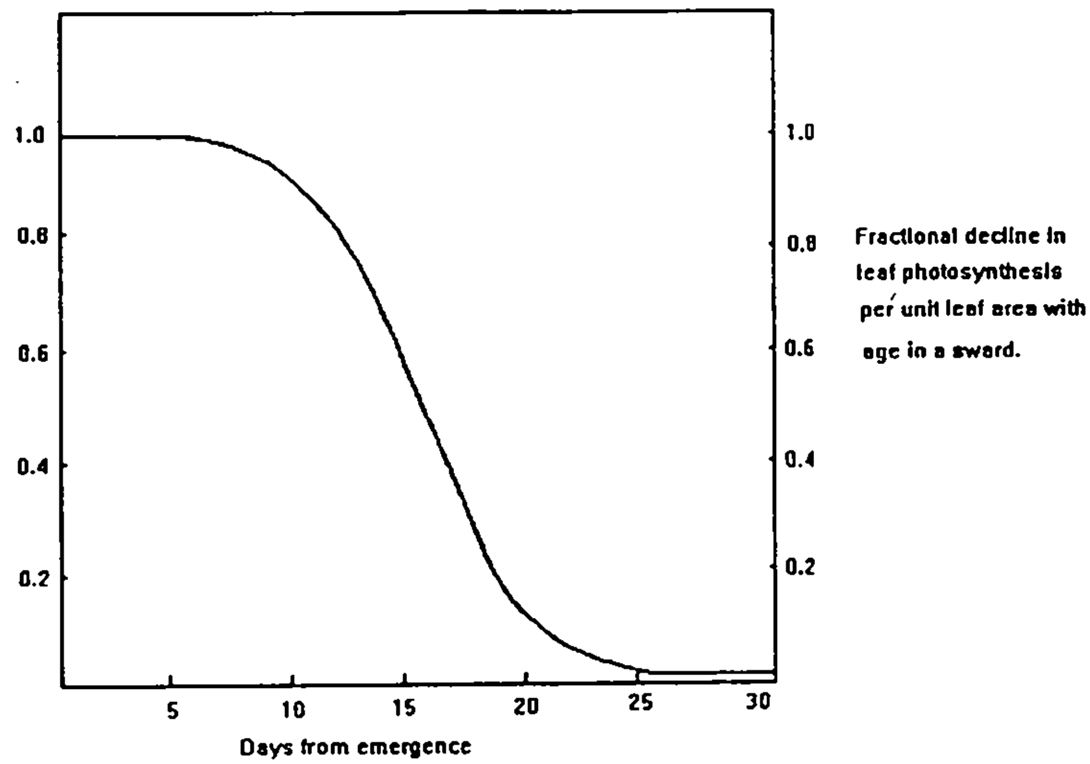


Figure 18 The decline in the rate of individual leaf photosynthesis per unit leaf area with age.

where Pmax(i) is the initial maximum rate of photosynthesis of leaf that emerged from the sheath on day i as calculated from Equation (17), Pmax(d) is the maximum rate on day d, D/2 is the time taken for the rate to decline by 50%, and D is the life span of an emerged piece of leaf. The relationship in Figure 18 is shown for D=30. This shows that for the first 10 days or so the rate of photosynthesis remains fairly constant, by D/2 or 15 days it has fallen to 50% of the initial value and has reached about 1% by day D=30.

Using the method of defining the life span of a leaf based on weight loss through respiration Equation (31) was modified by replacing the term exp[0.44(d-D/2)] by a term which depended on the weight of leaf after respiration. Thus;

$$Pmax(d) = Pmax(i)/(1{=}exp(50(0.6-f_t))) \tag{32}$$

where f_t is the respiratory factor described by Equation (30). This equation was largely derived from calculations made using the respiration model and showed that a piece of leaf lost about 40% of its initial weight half-way through its life span.

When running a model from some arbitrary point in time following defoliation the initial pattern of crop growth is largely a result of the physiological and morphological state of the crop before that time. To take account of this the grassland model is initialized by modelling growth for about 7 weeks before simulating a 'cut', by removing all expanded leaf. Subsequently, the second regrowth is studied in detail (1 April: day = 91).

6.2.6) Soil moisture and plant water loss

In the model soil moisture available to the grass crop is assumed to be in the top 30 cm of the soil profile (*i.e.* 30 cm maximum rooting depth). It is also assumed that of the daily input of rainfall to the soil moisture reserves 25% is lost through leaching.

Transpiration (ET; $gH_2O\ m^{-2}\ d^{-1}$) from the grass crop is calculated from the Penman-Monteith equation;

$$ET = \frac{sI_0\exp(-kL) + LVG(e_s(Td) - e)/r_a}{(s + G(r_a + r_s)/r_a)V} \tag{33}$$

where $I_0 exp(-kL)$ is the average irradiance ($J\ m^{-2}\ d^{-1}$) experienced by the canopy of leaf area index L, V is the latent heat of vaporization of water (V=2450.0 $J\ g^{-1}$), G is the psychrometric constant (G=0.5 $g\ m^{-3}\ (^{\circ}C)^{-1}$), Td is the daily mean temperature,[e_s(Td)-e] is the difference in water vapour pressure ($gH_2O\ m^{-3}$)between the ambient air (e) and the air at saturation [e_s(Td)], s is the rate of change of saturation vapour pressure with temperature ($gH_2O\ m^{-3}\ (^{\circ}C)^{-1}$) and r_a and r_s are the boundary layer and stomatal resistances to water vapour(s m^{-1}). Each day the amount of water transpired is subtracted from the soil moisture reserves.

6.2.7) Soil nitrogen uptake and recycling

The model calculates the daily soil nitrogen uptake by the grass crop (U; $gN\ m^{-2}\ d^{-1}$) from the equation;

$$U = DN-RCN(ndl+nds+ndr) \quad (34)$$

where DN (gN m^{-2} d^{-1}) is the daily demand for nitrogen, (ndl+nds+ndr) is the nitrogen content of dead leaf, stem and root tissue generated each day (gN m^{-2} d^{-1}) and RCN is the fraction of nitrogen recycled from dead tissue each day (RCN=0.85). In Equation (34), the daily demand for nitrogen is taken as the net daily gain of carbohydrate multiplied by the fractional nitrogen content of the crop f=0.03, a value typical of a grass crop under conditions of non-limiting soil nitrogen.

The uptake of nitrogen from the soil in Equation (34) is limited by a maximal uptake U' which takes into account the root density of the crop and the nitrogen content of the soil (SNC; gN m^{-3}). Using a form of the Michaelis-Menton equation;

$$U' = (1/(1/Vm+Rkm/SNC))Rd \quad (35)$$

where Vm is a maximum rate of uptake (=0.03 gN(g root)$^{-1}$ d^{-1}) and Rkm is a Michaelis-Menton type constant (=2.0X10^3 g root m^{-3} d^{-1}). In the model, if U>U' then U=U'. Nitrogen from dead tissue which is not recycled (15%) according to Equation (34) is returned to the soil nitrogen pool.

A routine is incorporated in the model which allows for the effect of plant nitrogen levels on photosynthesis. If the soil nitrogen reserves are depleted to such an extent that there is no nitrogen uptake by the crop (U=0) then the fractional nitrogen content of the crop f' is calculated as;

$$f' = RND/Wd \quad (36)$$

where Wd (gCH2O m^{-2} d^{-1}) is the net daily gain of carbohydrate and RND (gN m^{-2} d^{-1}) is the recycled nitrogen from dead tissue [=RCN(ndl+nds+ndr)]. When U>0 then f'=f. The effect of low plant nitrogen content on photosynthesis is modelled through its effect Pmax and is described by;

$$Pmax = Pmax.f'/f \quad (37)$$

Thus Pmax will be reduced in proportion to the reduction in plant nitrogen content.

6.3) Simulation

Environmental data collected from an automatic weather station in the Monachyle Glen catchment at Balquhidder, Scotland during 1990 (solar radiation, temperature, humidity and rainfall) have been used in the grassland model. Figures 19,20,21 and 22 illustrate the predicted effects of a 3°C mean temperature rise and a doubling of atmospheric CO_2 content (350-700 ppm) above ambient on leaf area index, canopy photosynthesis and dry matter production and partitioning. The four regimes used are:

(i) Normal temperature / 350 ppm [CO_2].
(ii) Temperature+3°C / 350 ppm [CO_2].
(iii) Normal temperature / 700 ppm [CO_2].

Figure 19 Canopy leaf area index.

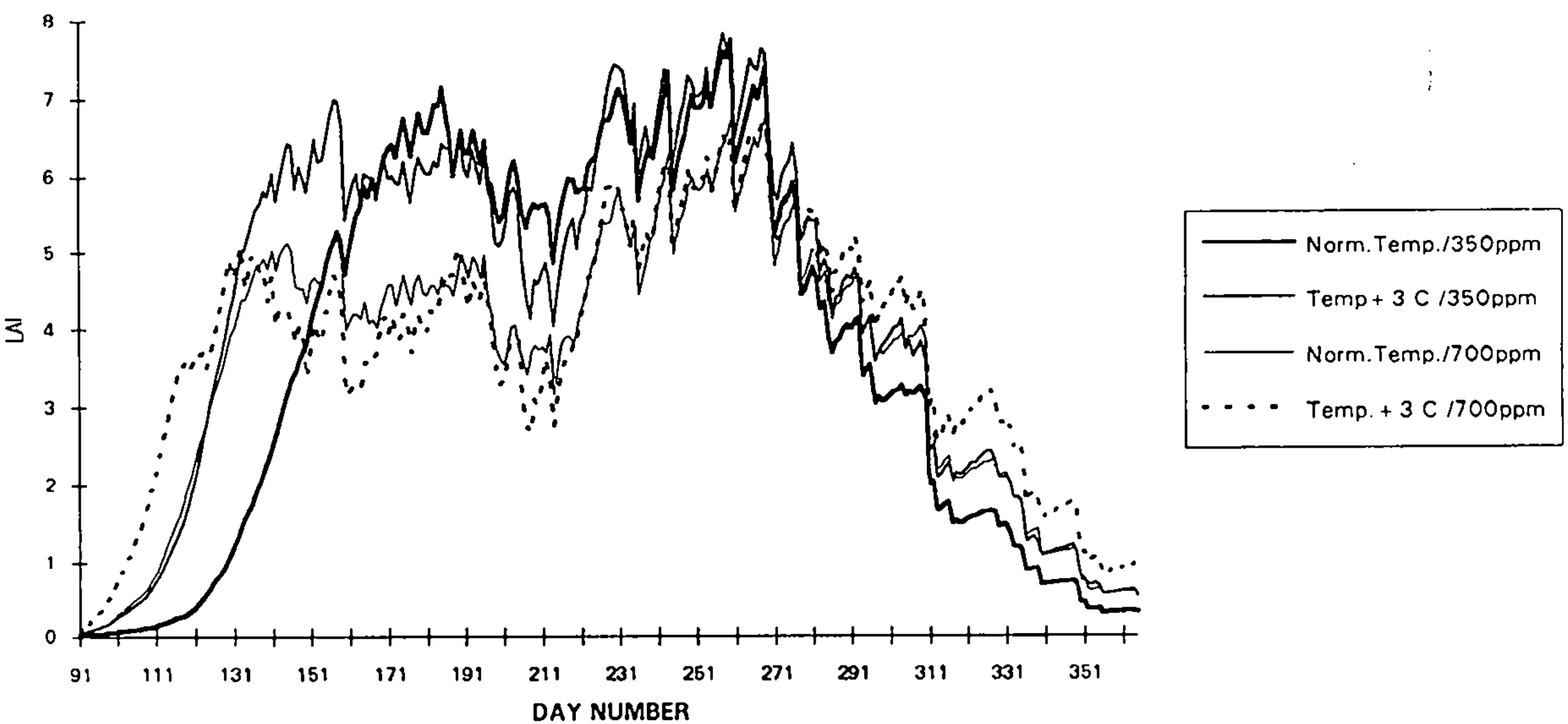


Figure 20 Canopy photosynthesis.

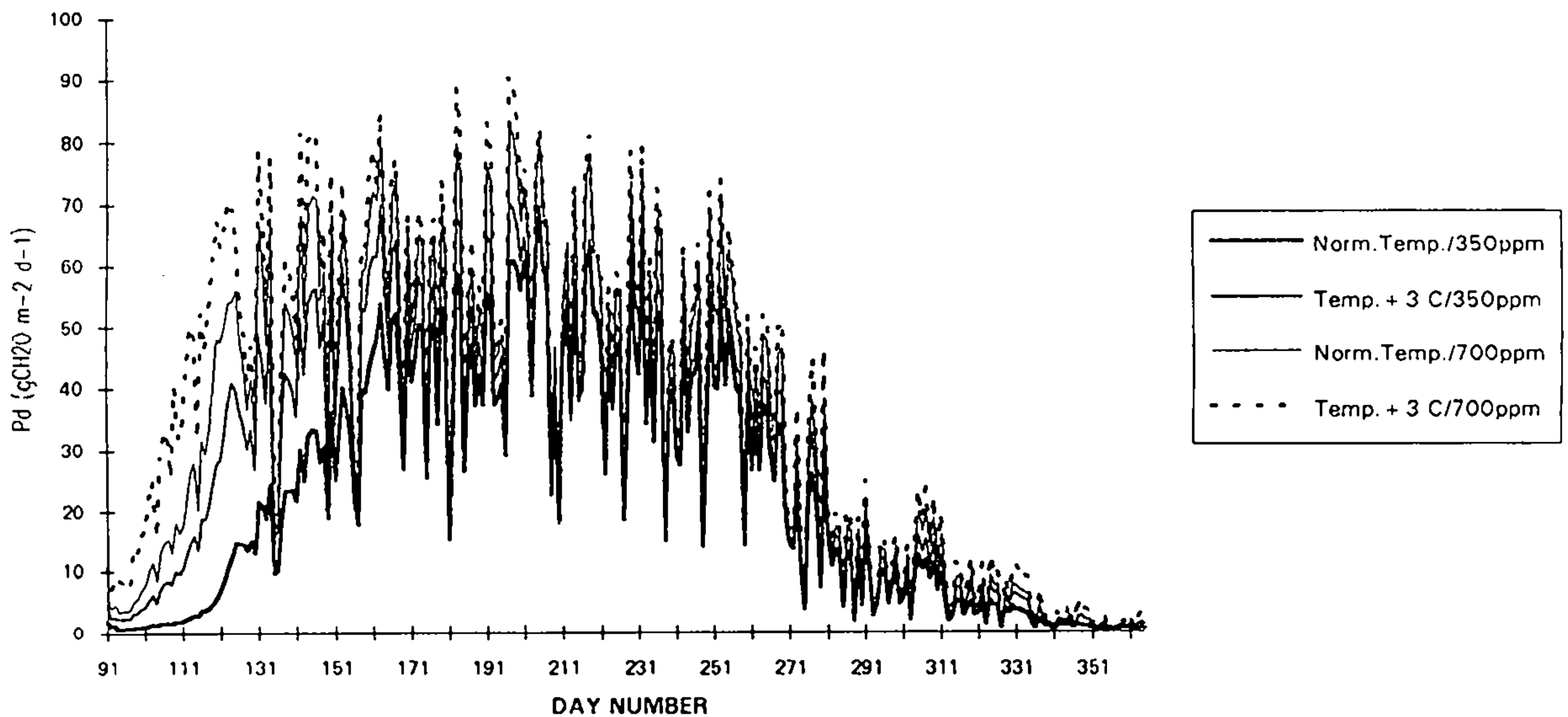


Figure 21 Total dry matter.

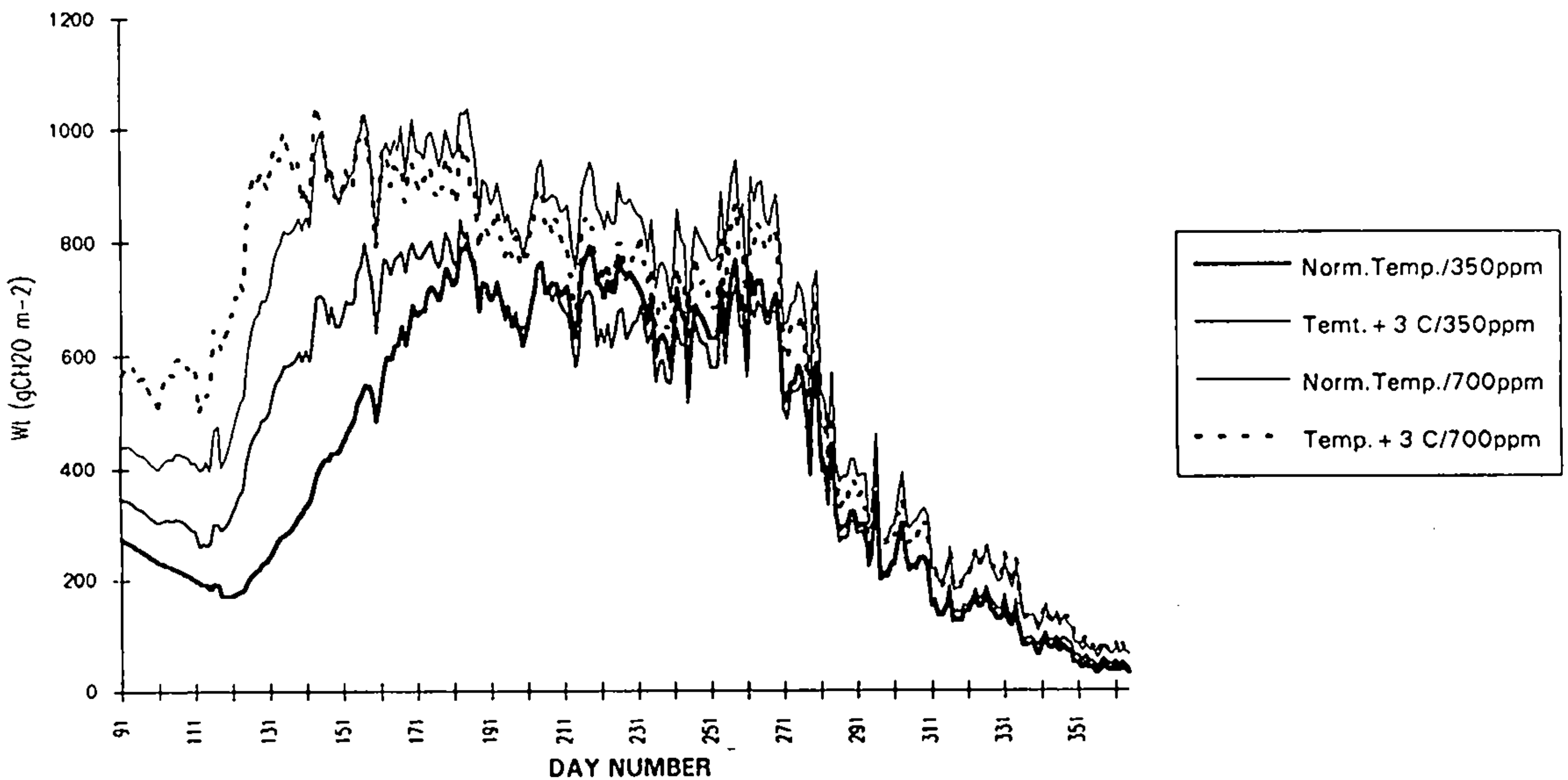
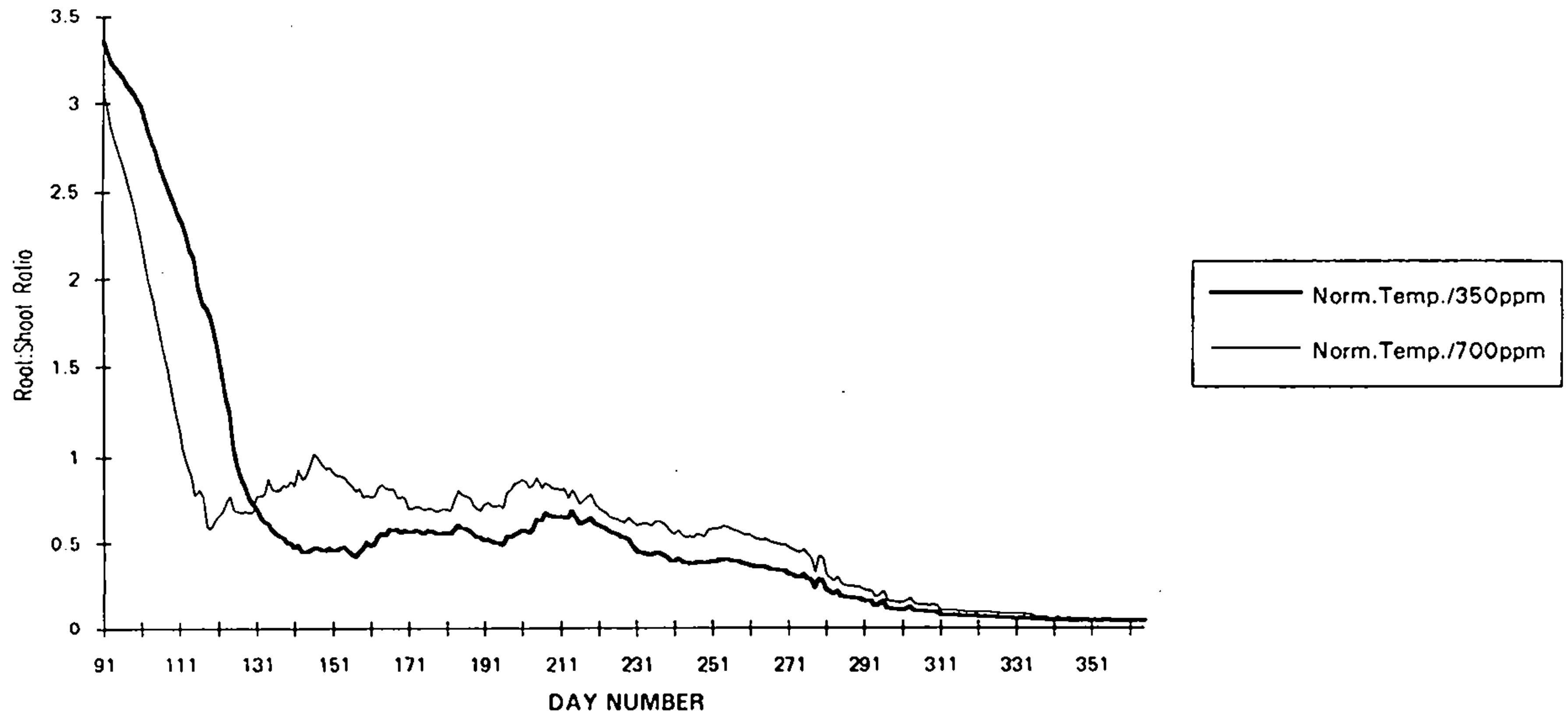


Figure 22 Root:shoot ratio of dry matter.



(iv) Temperature+3°C / 700 ppm [CO_2].

Compared to normal conditions, the increased temperature and CO_2 level regimes dramatically increase the rate of canopy formation, the duration of the exponential phase being shortened by about 30 days for regimes (ii) and (iii) and 40 days for (iv). These differential rates of canopy formation are also reflected in the results for canopy photosynthesis and dry matter production (Figures 20 and 21). However, for a given LAI, the fertilization effect of elevated CO_2 levels on photosynthesis and dry matter production is clearly evident. For example, at day 125 when LAI is about 4 for regimes (ii) and (iii) the values of canopy photosynthesis are about 40 and 55 $gCH_2O\ m^{-2}\ d^{-1}$ and dry masses about 400 and 650 $g\ m^{-2}$, respectively.

An interesting feature to emerge from the simulations is that smaller canopy sizes are produced at elevated CO_2 levels compared to those at 350 ppm. A possible explanation offered by the results from the model is that at elevated CO_2 levels a smaller proportion of assimilate is partitioned into leaves and stem in favour of root growth (Figure 21). During the period of maximal LAI's the root : shoot ratios at 700 ppm are 20 to 100% higher than those at 350 ppm CO_2, a result consistent with reports in the literature [1,3,16].

The seasonal distribution of dry matter production for all regimes (Figure 22) is similar to that reported for pure swards of grasses as shown in Figure 23. Two distinct peaks of production are evident, the first in early summer being higher than the second during late summer. The midsummer depression of dry matter production is generally the result of lower leaf area indices (Figure 19) and low photosynthetic potential of older shaded leaves and can be intensified by high temperatures and water stress and nutrient deficiency [34].

6.4) Future work

With the integration of the grassland and hydrochemical models a vegetation model will be developed which will be capable of long term transition between two possible states, a treeless pasture and a second woodland/forest as a result of migration/extinction of tree species.

7) Calibrating the Birkenes hydrochemical model

Given the problems encountered with the use of a semi-distributed hydrological model (Section 4 and 5), the requirement for a hydrological model within the linked model framework has focused on the lumped conceptual formulations. These models represent a catchment rather simply, usually as a series of reservoirs, with crude flow-routing. In many cases the dynamics of such models cannot be linked to real hydrological processes, hence they are termed conceptual. One model which has received much attention at IH for use in acidification research is the Birkenes model, a flow and water quality simulation tool. In the first instance, the Birkenes model has been fitted to the Upper Monachyle catchment at Balquhidder. Given an adequate calibration and validation it will be possible to assess the

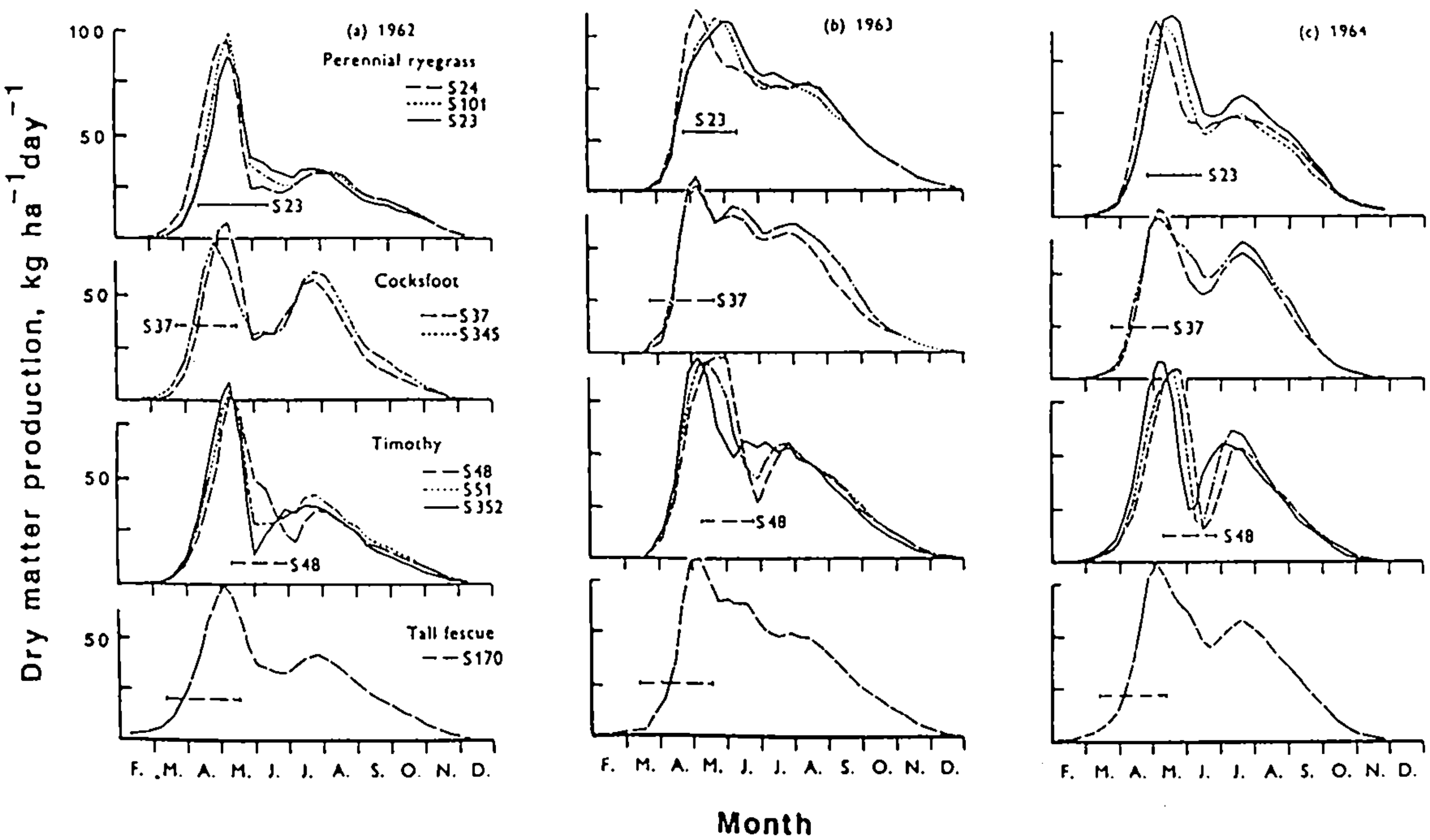
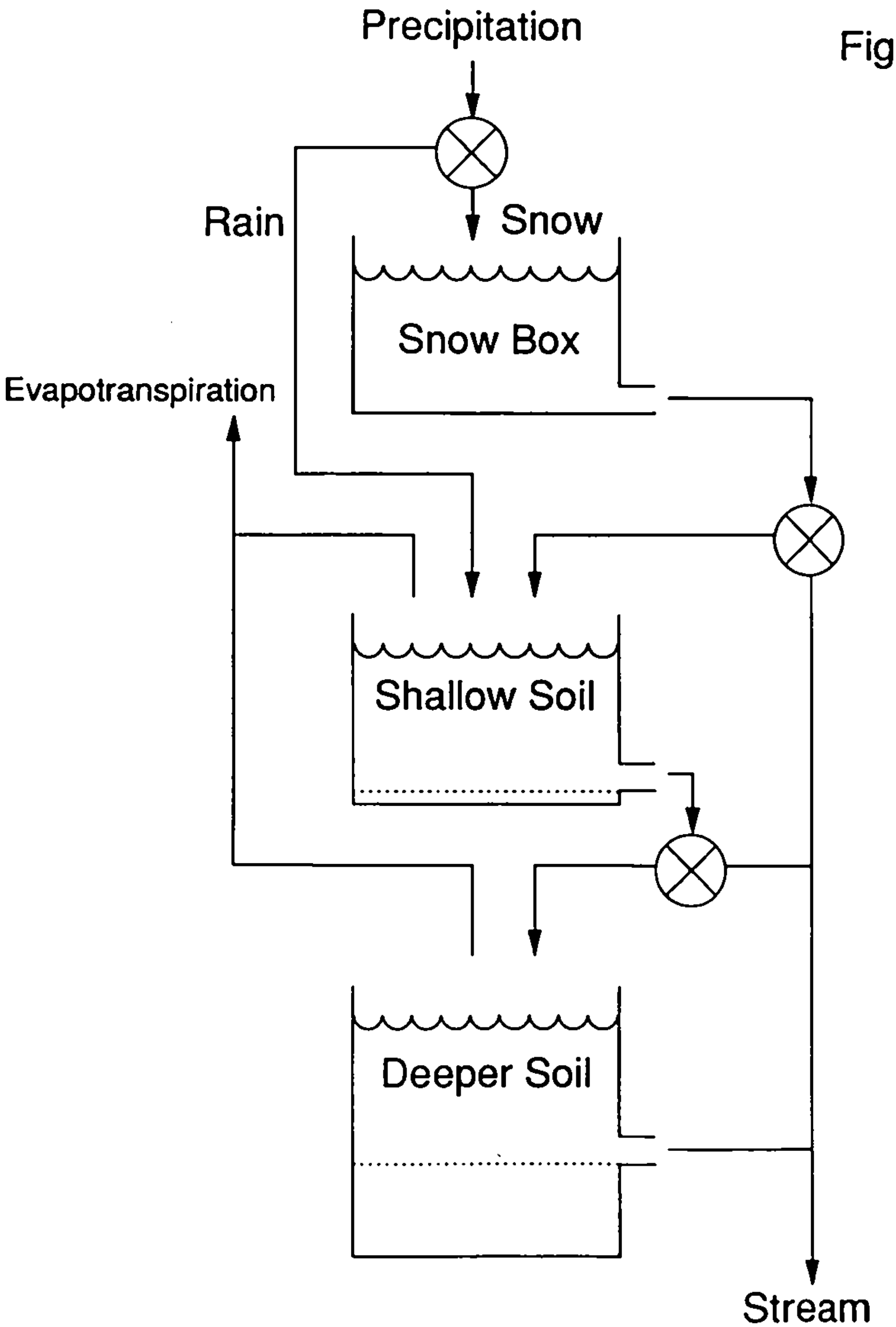


Fig 23 The seasonal distribution of dry-matter production of pure swards of several cultivars (S24 etc.) of four grass species grown in Southern England during three seasons. The horizontal bars indicate the period from initiation to emergence of inflorescences of one cv. per species (adapted from Anslow and Green 1967).

Figure 24


Precipitation
Rain
Snow
Snow Box
Evapotranspiration
Shallow Soil
Deeper Soil
Stream

suitability of the structure to climate change impacts research and it can then be linked to the other sub-models.

7.1) Description of the hydrology model.

The Birkenes model [9] is a lumped catchment model, which simulates flow and water quality. It has traditionally been applied on a daily time scale although has been tested at shorter (hourly) time scales [ref]. The model was constructed to simulate short-term variations in stream chemistry and so may be of indeterminate use for long-term climate change studies as it will be unable to simulate the long term dynamics of a catchment. Figure 24 shows a schematic diagram of the hydrological processes within the model. Precipitation falls as snow or rain dependent upon the air temperature. The snow melt can drain into the stream or the upper soil reservoir. The upper soil reservoir drains to the stream and the lower soil reservoir and the lower soil reservoir drains to the stream. Evapotranspiration is calculated from daily temperature values, although this parameter is often optimized to obtain a good fit of observed to predicted flows. Evapotranspiration is removed initially from the upper soil reservoir followed by the lower soil reservoir when the upper drys out. Within each soil reservoir water chemistry is determined by a set of ion exchange reactions and water is routed to the stream governed by the values of the hydrological routing parameters (marked X in Figure 24).

7.2) Calibration of the Birkenes model at Balquhidder.

Figure 25 shows the results of the initial fit of the Birkenes model to the Upper Monachyle gauging station within the Balquhidder catchment. The simulation follows the flow regime quite well. The two periods where no flow peaks appear in the predictions but appear in the observations are accounted for by the absence of a rainfall record for those periods (around day 100 and 300). The spikes in the stream flow in the observed record are predicted in the simulation, but are generally under estimated. This could be for a number of reasons, but was probably because of an under estimation of flow from the upper soil reservoir to the stream. The under estimation of flow from the upper soil reservoir allows the upper soil reservoir to hold more water than would otherwise be the case. This has implications for the linked vegetation and nitrate model in that the amount of water available to the grassland model would be over estimated as would the amount of nitrate available to the grassland model. This in turn would produce a greater biomass which would feed back causing a greater uptake of water. Further work aimed at improving this calibration is under way.

At present no attempt has been made to predict the stream chemistry of the Balquhidder catchment using the Birkenes model, however the data is available and this will be completed soon. Following the successful application of the Birkenes model, it will be linked with the vegetation and nitrate models.

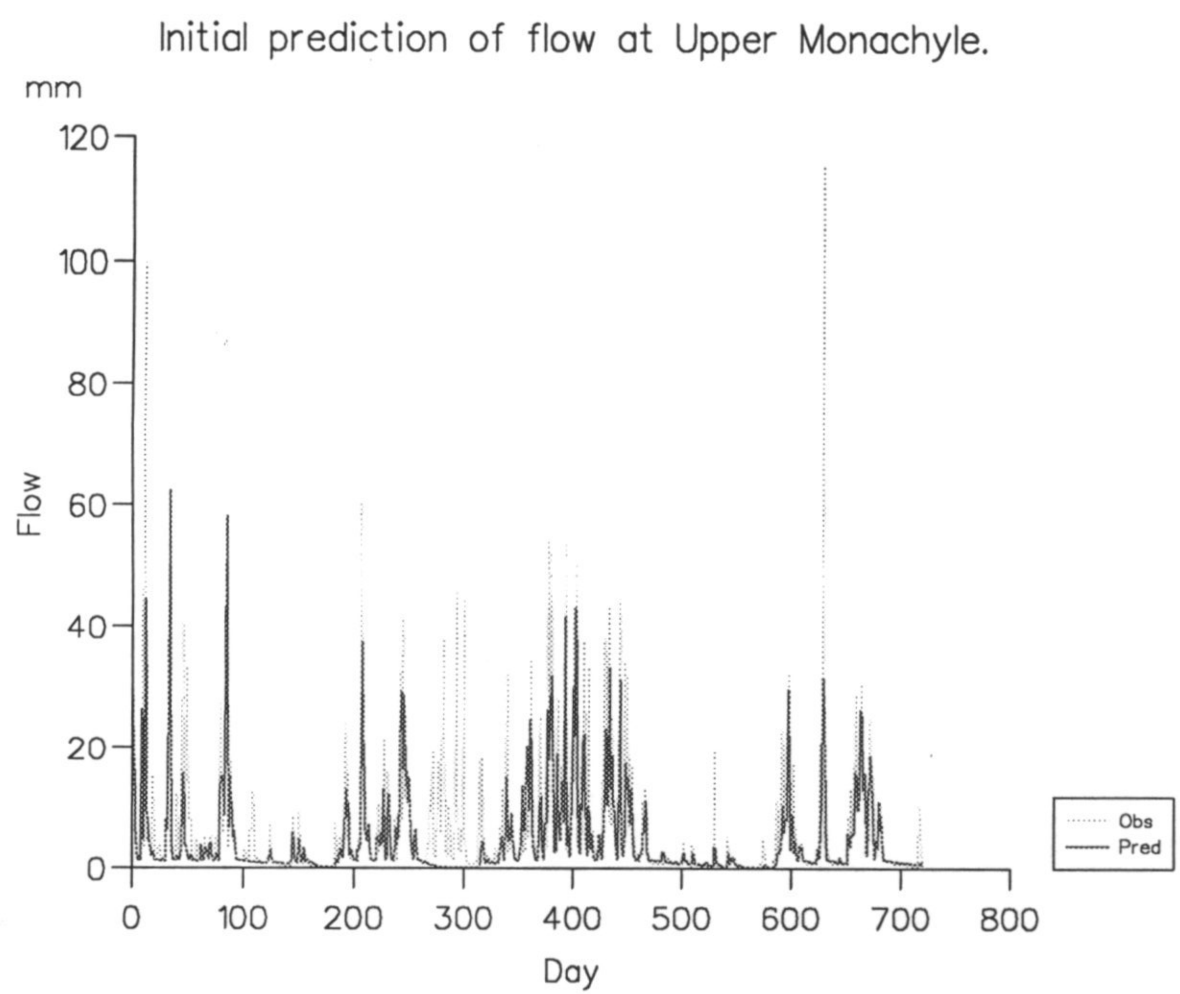

Initial prediction of flow at Upper Monachyle.
mm
120
100
80
60
40
20
0
Flow
0
100
200
300
400
500
600
700
800
Day
Obs
Pred

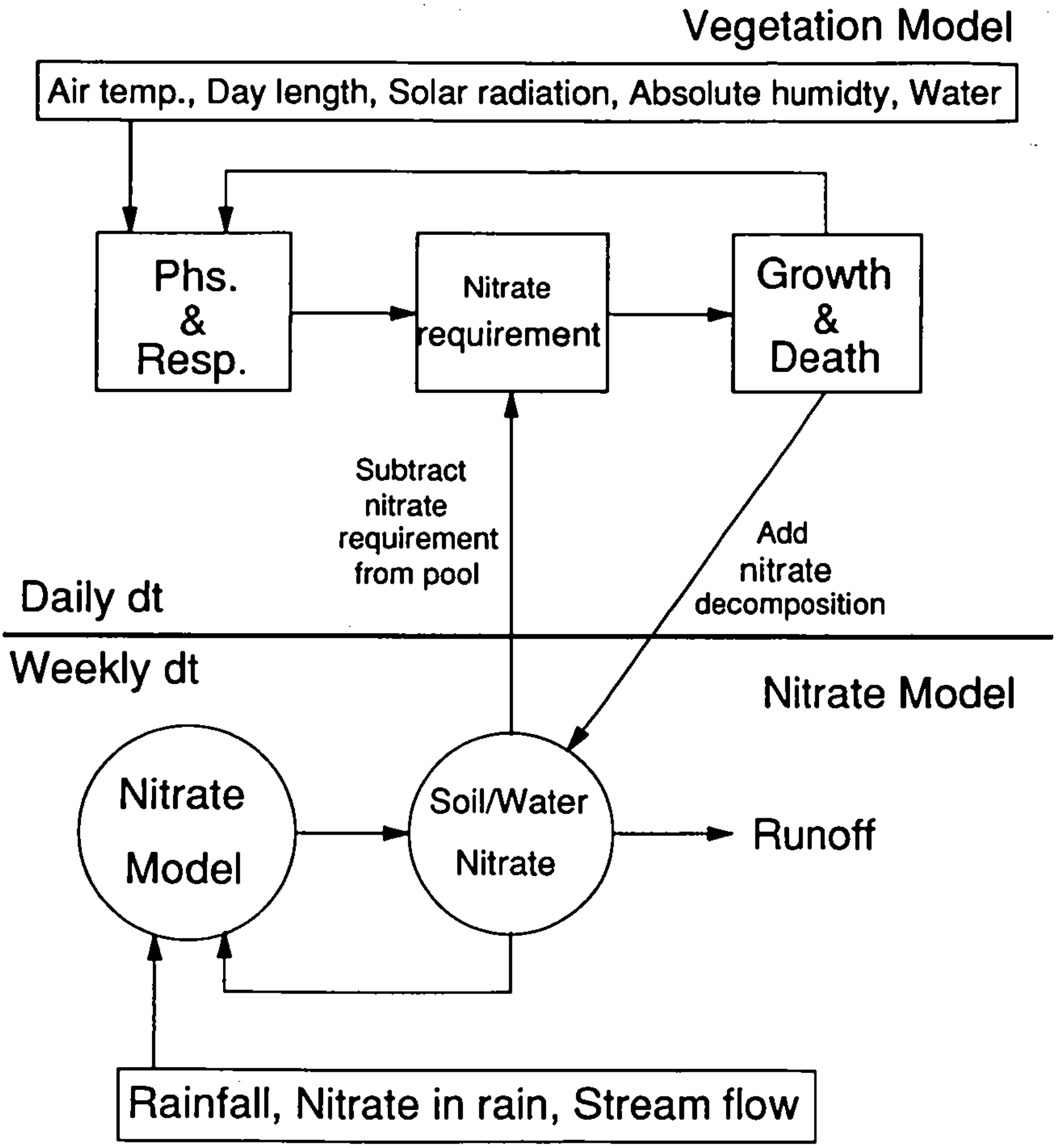
Figure 25

8) Linkage of the vegetation model to a simple nitrate model

As describe in Section 6, the vegetation model (or grassland model) has a requirement for nitrate from the soil water. The hydrology and soil water chemistry model described in section 7 does not model nitrate concentration in the soil water and so it is necessary to combine a specific nitrate model into the linked model. At this stage, given that other sub-models may prove inappropriate and so may be replaced by other structures, a simple mass balance model was used to model nitrate concentration in the soil water and it was assumed that the concentration in the soil water was the same as that in the stream. The model consists of a mass balance term for nitrate received and exported from the catchment and terms for mineralization and plant uptake, both a function of temperature.

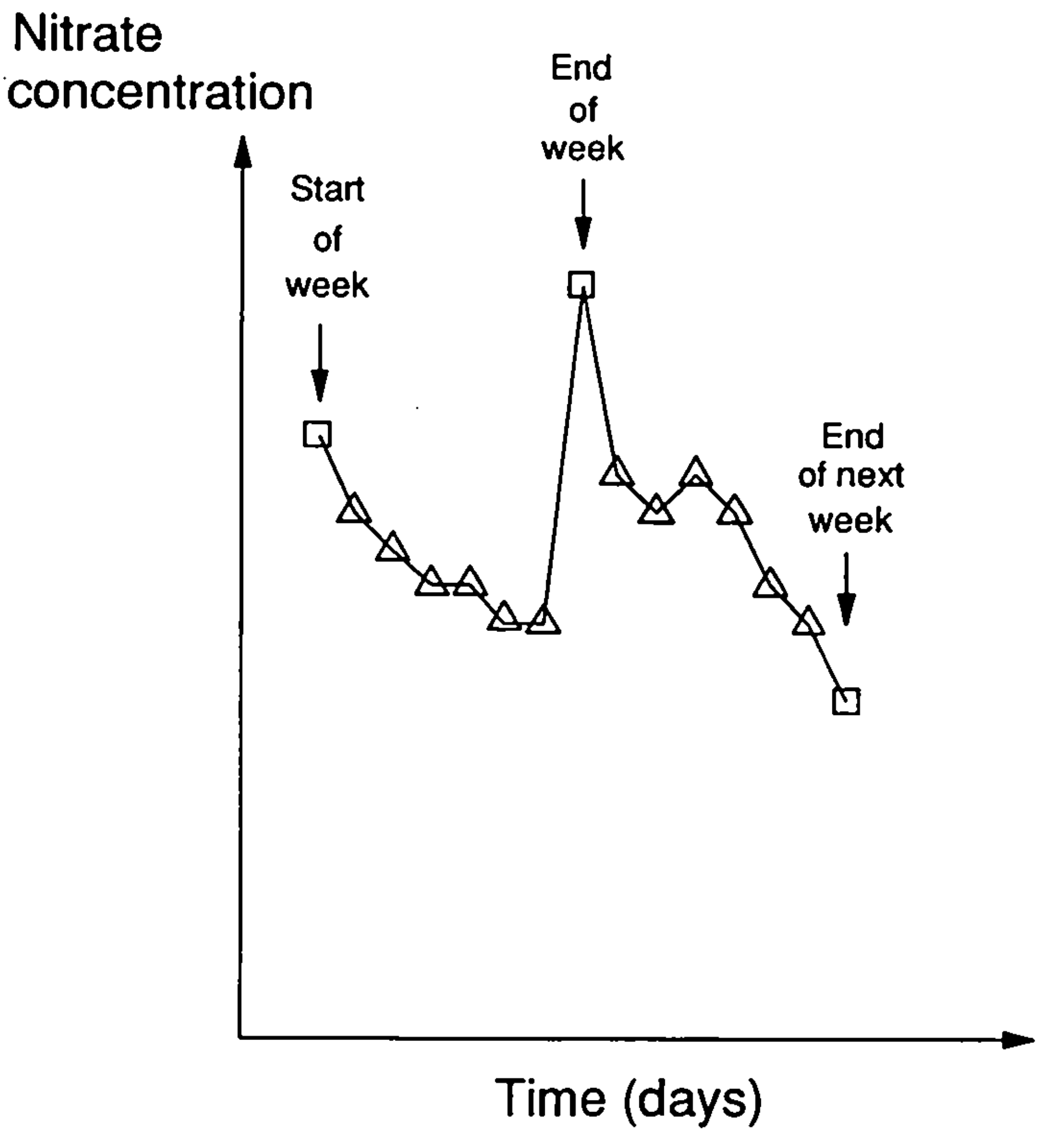
Figure 26 shows the linkage between the vegetation model and the nitrate model. The vegetation model runs on a daily time step (with an hourly routine for photosynthesis and respiration), whilst the nitrate model runs on a weekly time step. The two conflicting time steps are reconciled by nesting the nitrate model within the vegetation model and running a time step of the nitrate model every seventh day of the vegetation model. The vegetation model has a requirement for nitrate each day and returns a certain amount of nitrate into the soil water each day from the decomposition of leaf litter. It is assumed that there is no delay between the production of dead organic material and the incorporation of nitrate from dead matter into soluble form. It is also assumed that if there is sufficient nitrate in the soil/water phase to meet the demands of the vegetation model for a given day, then all of that nitrate is available to plants. The nitrate remaining in the soil water pool at the seventh day, is used in the calculation for the next weekly time step of the nitrate model. Figure 27 shows the expected change in nitrate concentration over a two week period. At each daily time step an extraction and addition were made to the nitrate concentration in the soil water (Figure 27) and at each weekly time step the soil water nitrate concentration was recalculated using the present day's concentration as an input value to the model.

Figure 28 shows the observed nitrate concentrations in the Hafren stream at Plynlimon. The seasonality of the nitrate signal dominates, with high nitrate concentrations in winter, because of the low plant uptake and low mineralization , and low nitrate concentrations in summer with high plant uptake despite high mineralization rates. The nitrogen concentration in the stream has been simulated using the linked nitrate and vegetation model (Figure 28). The predicted nitrate concentration follows the seasonal trends seen in the observed signal, with peaks during winter and troughs during summer. The predicted nitrate concentrations in winter are of similar magnitudes to observed values, but summer values are approximately 0.5 mg/l lower. This is because nitrate uptake by plants is accounted for twice and so uptake during the summer growth period was greatly exaggerated. The nitrate model is a simple regression model with a generalized term which accounts for all nitrogen dynamics within the nitrogen cycle, such as mineralization, nitrification and extraction by plants. Thus, at present, extraction of nitrate by vegetation is accounted for twice, once within the nitrate model and again as uptake by plants in the vegetation model. At present the nitrate model cannot be broken down into individual nitrogen processes occurring within the soil/water matrix, however, when this is accomplished the vegetation uptake term will be removed from the nitrate model and so correcting this problem of double accounting. Figure 29 shows the



Vegetation Model
Air temp., Day length, Solar radiation, Absolute humidty, Water
Phs. & Resp.
Nitrate requirement
Growth & Death
Subtract nitrate requirement from pool
Add nitrate decomposition
Daily dt
Weekly dt
Nitrate Model
Nitrate Model
Soil/Water Nitrate
Runoff
Rainfall, Nitrate in rain, Stream flow

Figure 26



△ Change in concentration because of plant extraction and decomposition.

□ Change in concentration because of plant and nitrate model steps.

Figure 27

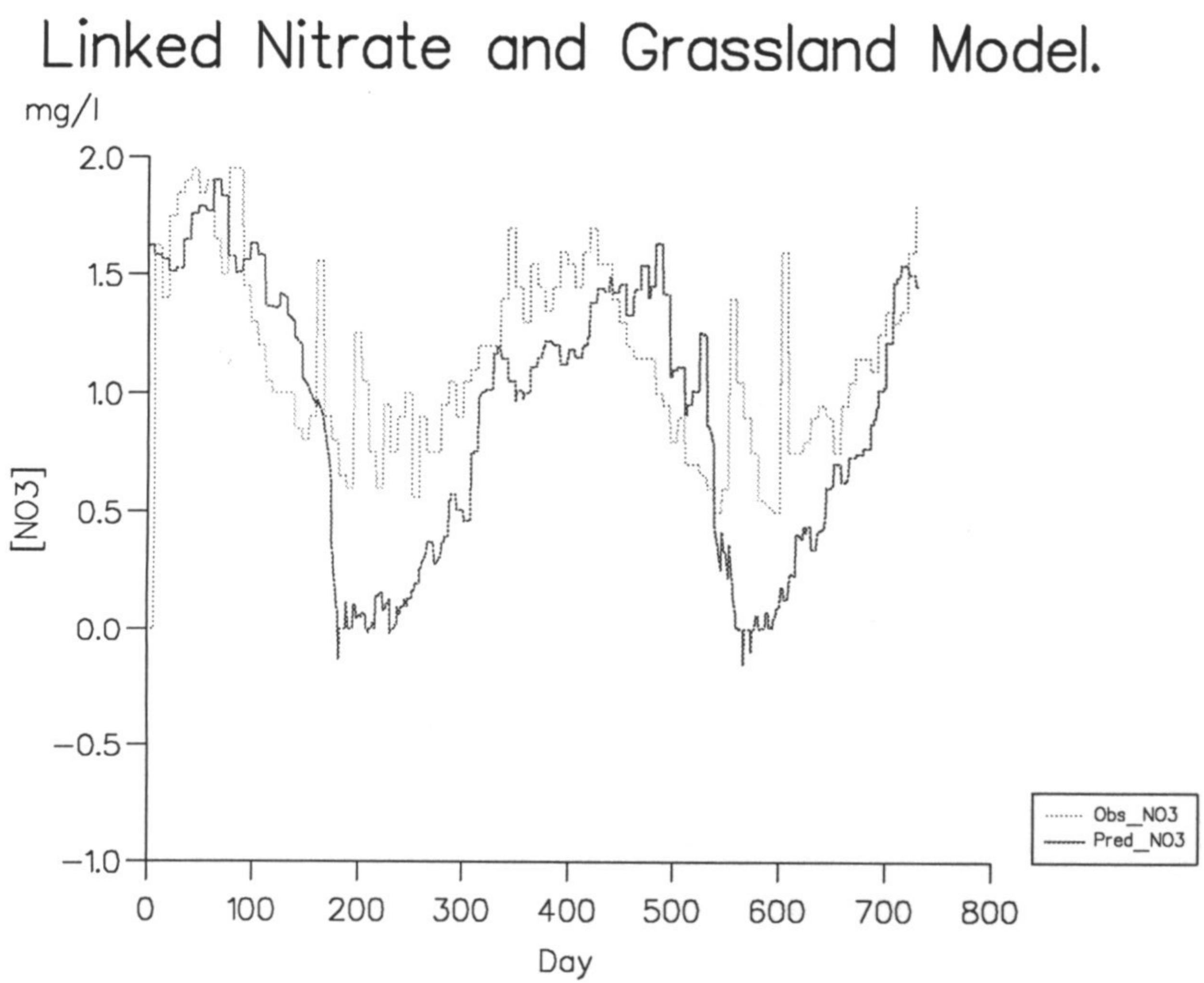

Linked Nitrate and Grassland Model.
mg/l
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
[NO3]
0
100
200
300
400
500
600
700
800
Day
Obs_NO3
Pred_NO3

Figure 28

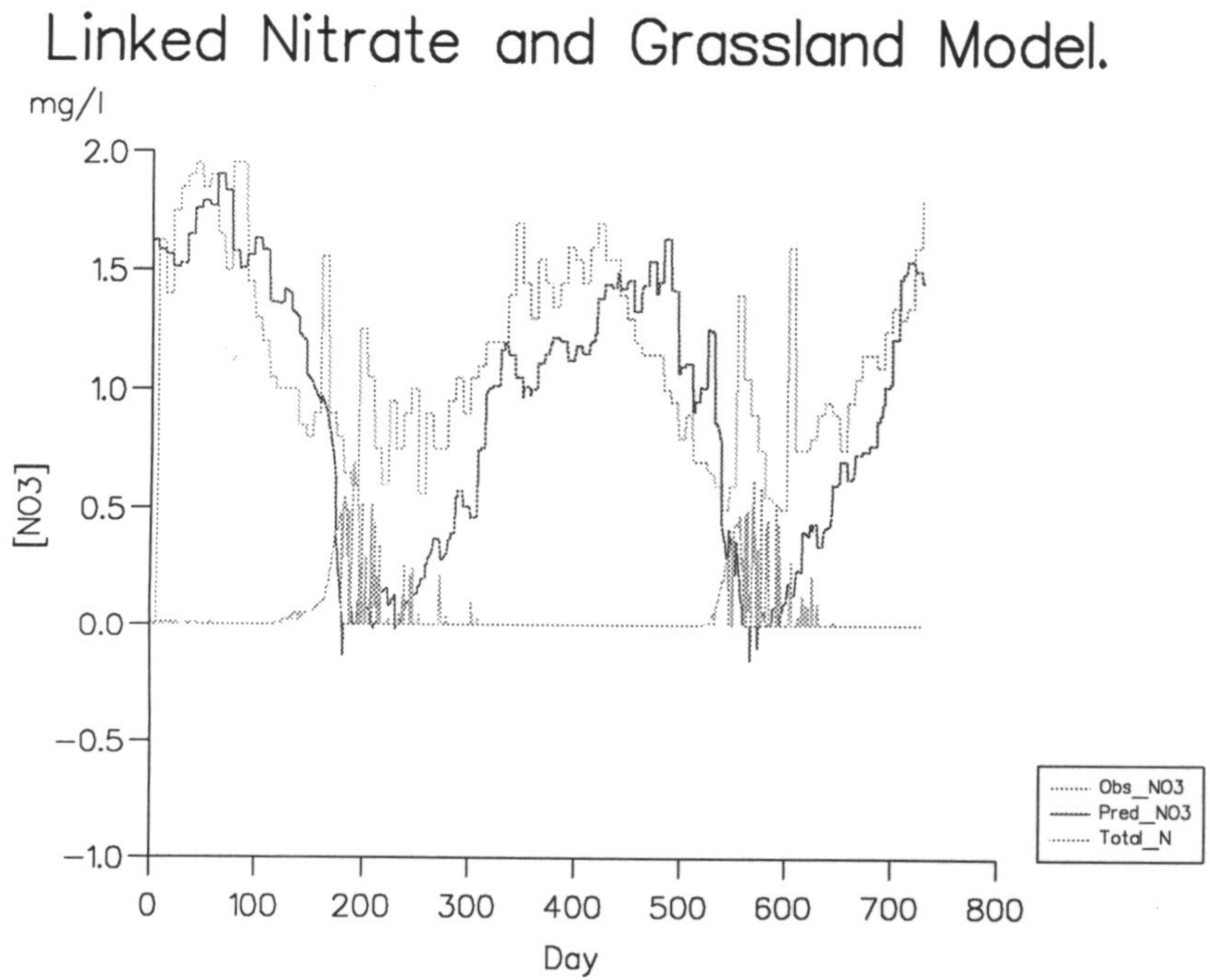

Linked Nitrate and Grassland Model.
mg/l
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
[NO3]
0
100
200
300
400
500
600
700
800
Day
Obs_NO3
Pred_NO3
Total_N

Figure 29

observed and modelled nitrate concentrations in the stream along with the total nitrogen uptake by the vegetation model.

It must be stressed that this application was an exercise aimed at linking the model structures and not for accurately simulating observed concentrations since the grassland model cannot be expected to adequately represent a mature forest system. Data from moorland catchments will be obtained for true model validation.

9) Difficulties in coupling models

No account has yet been made of the water balance within the linked nitrate and vegetation model. The vegetation model was considered to have all the water required for growth and so was never under water stress. The nitrate model required stream flow data as an input and the water was considered separately from the water in the vegetation model.

In order to achieve the project objectives, it will be necessary to couple hydrology and water chemistry with the nitrate and vegetation models. When this is achieved, the nitrate requirement of the plants, can only be meet from the supply of water taken up by the plant *i.e.* the vegetation will be unable to extract nitrate direct from the water in the soil but will remove it from the water once the water is inside the plant. This implies that if there is no water available to the plant then no nitrate will be available and the plant would be under water and nitrate stress.

Figure 30 shows a schematic of how the three components of the linked model will be coupled. The methodology will be based on the linkage between the nitrate model and the vegetation model that already exists (Figure 26). The linked model will run at three time scales. The photosynthetic and respiratory routines within the vegetation model will run on an hourly scale and the results summed to a daily scale for use in the vegetation model which runs on a daily scale. The vegetation model will access the nitrate and water stores from the nitrate and water pools produced by the hydrology and nitrate models on a daily basis.

The linked hydrology, water chemistry and grassland model will firstly be implemented on a daily time step and will be modified by output from the nitrate model on a weekly basis. This will produce an amount of water in the upper soil reservoir accessible to the plant and a water chemistry for the stream. Once the plant has extracted the water required for that day the upper soil reservoir can become completely dried out. This presents a problem in that the existence of water in the upper soil horizon does not mean that it is available to the plant. As the soil reservoir drys out the water should become increasingly difficult to remove. The easiest way to implement this would be to place a limit on the amount of water that can be extracted, below which the plant is unable to extract the water, despite there still being water in the soil. A more accurate way to represent this process would be to represent the amount of water that can be extracted from the soil as a hyperbolic function, with a maximum limit on the amount of water that can be extracted. As the amount of water in the soil decreases

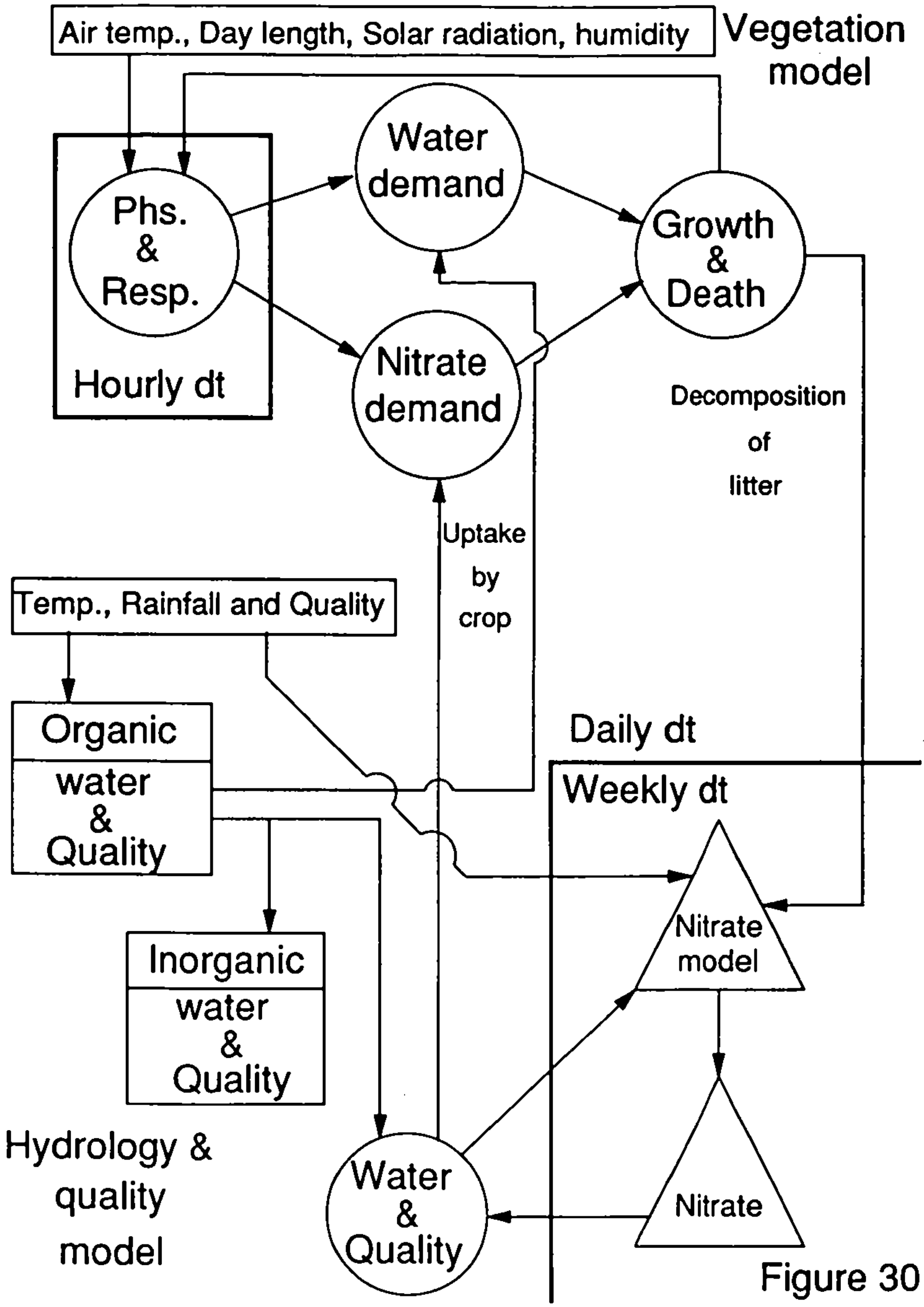

Air temp., Day length, Solar radiation, humidity
Vegetation model
Water demand
Phs. & Resp.
Growth & Death
Hourly dt
Nitrate demand
Decomposition of litter
Uptake by crop
Temp., Rainfall and Quality
Organic
water & Quality
Daily dt
Weekly dt
Nitrate model
Inorganic
water & Quality
Hydrology & quality model
Water & Quality
Nitrate

Figure 30

the quantity that can be extracted decreases, with a sharp decline in the amount of extractable water available below a certain quantity of water in the soil. These concepts represent known physical processes in soils and so can be relatively easily incorporated into the hydrological - vegetation linkage.

The hydrology and water chemistry model is driven by rainfall and rainfall quality. The results of the hydrology model will be modified by the vegetation model, in that water will be extracted, if available, as required. It is assumed that nitrate, and other ions in the water, will be the only nutrients available to the vegetation model. That is, the grassland model will have no other method of extracting nutrients from the soil or air other than by utilizing what is available in the water. This assumes no active uptake of ions independent of water uptake. It will also be assumed that the root length of the grassland is not sufficient to reach the lower soil reservoir and so extracted water and nutrients will come solely from the upper soil reservoir. The water in the upper reservoir will also be affected by evaporation from the leaf surface and soil surface, which will be temperature dependent. It will also be assumed that there is no chemical interaction between the nitrate ions and the other nutrients in solution.

The nitrate model will be driven by the results of the hydrology model, concentration of nitrate in rain and temperature. There will also be nitrate input from the decomposition of leaf litter from the grassland model.

The vegetation model will require climatic driving variables as well as water, nitrate and other nutrients from the water quality model. This will produce feedback into the nitrate model from leaf litter decomposition.

There will be many other feedbacks as well as those mentioned here, within the linked model which will combine to form a complex non-linear system. Once the coupled model is completed it will be calibrated to the Balquhidder catchment and the results will be compared with observed data.

10) Menu system for Impacts study

To apply climate change scenarios to the individual and linked models developed within the project and to simplify the application of models applied to UK catchments a menu system has been designed. The menu system developed allows the climate change impacts researcher (the 'user') to select a climate change scenario, a model and an area in which to apply the scenario. The system links GIS, database and models together and these software links are invisible to the user. The GIS employed is Arc/Info, the relational database is Oracle and the models are developed in Fortran. It is at present possible to link Arc/Info to a database (external to the GIS) using the facilities within Arc/Info. This allows access to the current data without having to convert the data from the current format into an Arc/Info coverage format, although an Arc/Info coverage has to be present with items that can be related to the tables within the database, *e.g.* a catchment identity number. It is not yet possible, however, to link complex catchment scale models to Arc/Info as the 'Object Code Licence' has not yet been received for Arc/Info under the CHEST agreement. Simple regression models can be included utilising the macro language facility (AML) within Arc/Info (*e.g.* SMD case study [11]). The menu system is written in the Arc/Info AML and can be used to display datasets and select and display data for a particular catchment/s.

10.1) The start menu

The menu system is started from the command line at the Arc/Info prompt. Figure 31 shows the starting menu presented to the user. The menu appears as a window at the top right-hand corner of the workstation screen, with a background window filling most of the screen for displaying the results of commands and another window at the base of the screen for text messages. The user is presented with five iconized 'buttons' which are activated with the mouse. Four options activate the sub-menus and the 'Exit' option finishes the session and returns the user to the Arc/Info prompt. Selection of any option activates the sub-menu which replaces the starting menu in the top right-hand corner of the screen.

10.2) The plot menu

At the 'Plot' menu (Figure 32) the user can select data of interest. A background UK dataset can be chosen *e.g.* Land use, HOST or altitude in grid or polygon formats. These formats refer to the composition in which the datasets are stored within Arc/Info. A number of features can be plotted over these background datasets, including; UK hydrometric areas, UK gauged catchment areas and the UK river network.

If the zoom facility is activated cross-hairs appear on the displayed map and the mouse can be used to augment the chosen area to be enlarged. The data is then redisplayed at the maximum scale for the screen. The 'Zoom' option can be used repeatedly. The reset button resets the box back to the UK scale and clears the screen, but does not re-plot the chosen options. The 'Clear' option, clears the screen, without changing the current scale. The exit option returns the user to the start menu leaving the current screen unchanged.

10.3) The model menu

Selection of the 'Model' option replaces the start menu with five icons representing (Figure 33) different models, including; a vegetation model, a hydrochemical model (Birkenes), two hydrological models (TOPMODEL and IHACRES) and the linked model (hydrology, water chemistry and vegetation models). The exit button returns the user to the 'Start' menu.

10.4) The climate menu

The 'Climate' option at the start menu selects the climate menu (Figure 34) with three icons and the 'Exit' option which returns the user back to the 'Start' menu. Each of the three options set a flag as to what climate scenarios the model will use. At present there is a choice of three; present day equilibrium climate at 340 ppm [CO_2], a future equilibrium climate at 780 ppm [CO_2] and a transient climate scenario where the climate changes from a present day [CO_2] to a future [CO_2] in some predescribed manner.

Figure 31

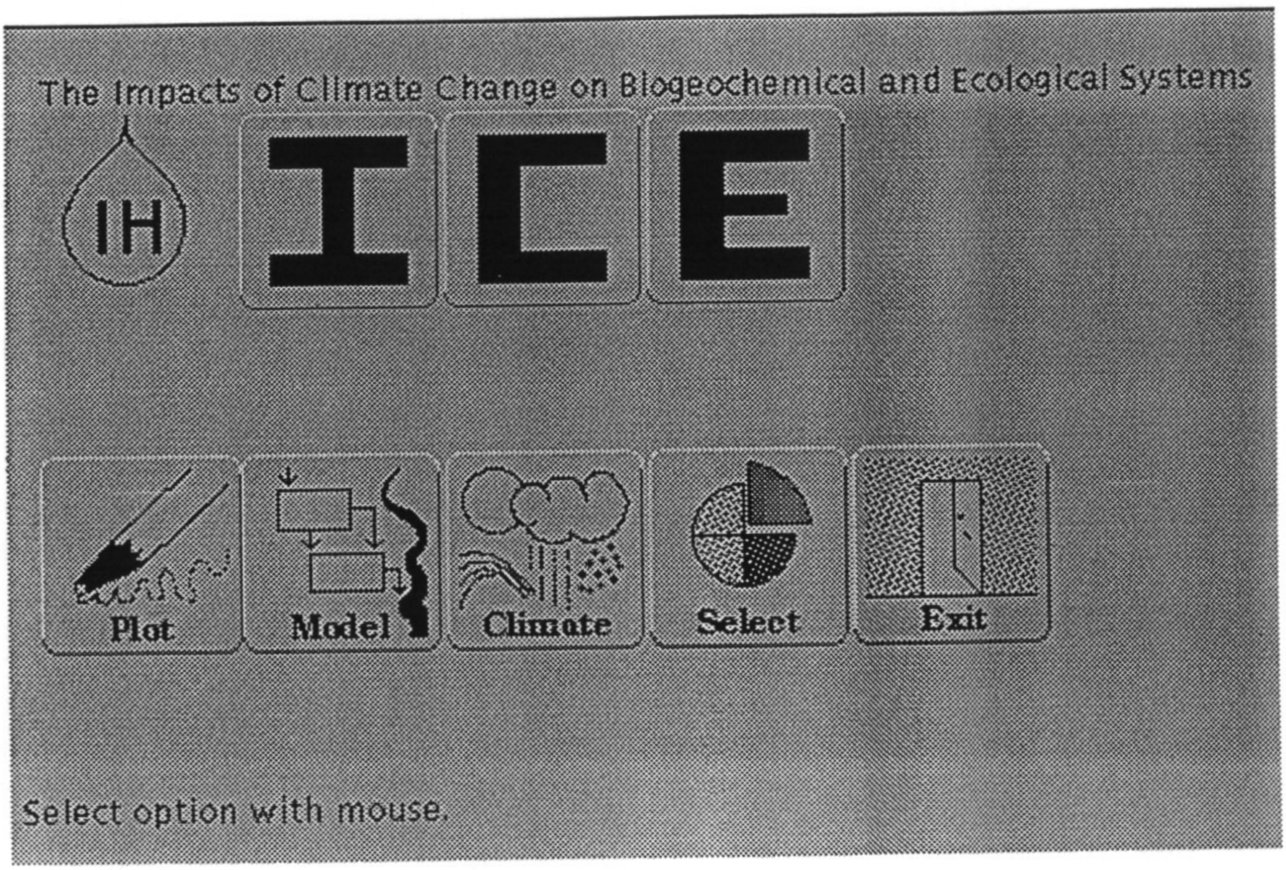
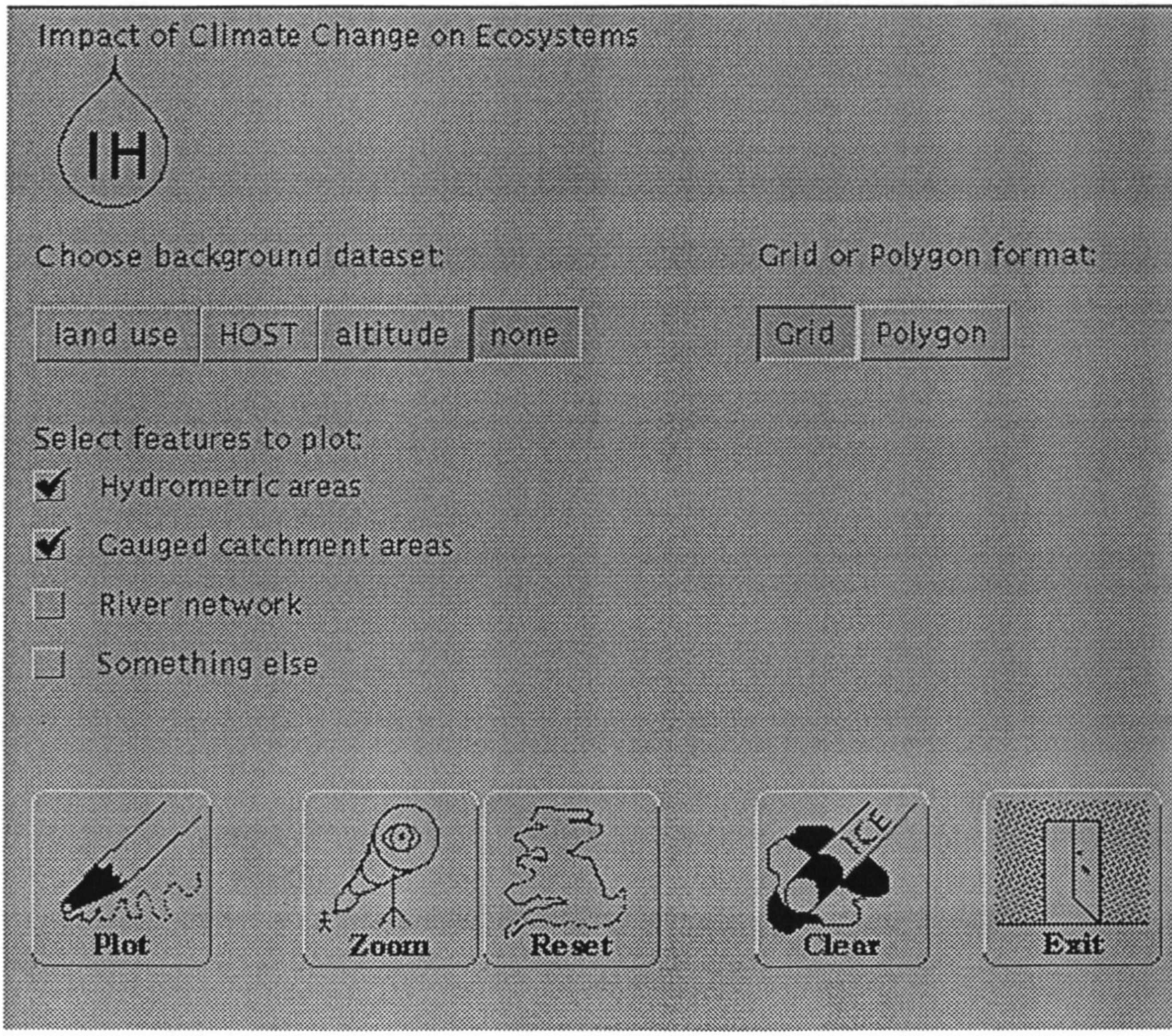

The Impacts of Climate Change on Biogeochemical and Ecological Systems
IH
ICE
Plot
Model
Climate
Select
Exit
Select option with mouse.

Figure 32



Impact of Climate Change on Ecosystems
IH
Choose background dataset:
land use
HOST
altitude
none
Grid or Polygon format:
Grid
Polygon
Select features to plot:
Hydrometric areas
Gauged catchment areas
River network
Something else
Plot
Zoom
Reset
ICE
Clear
Exit

Figure 33

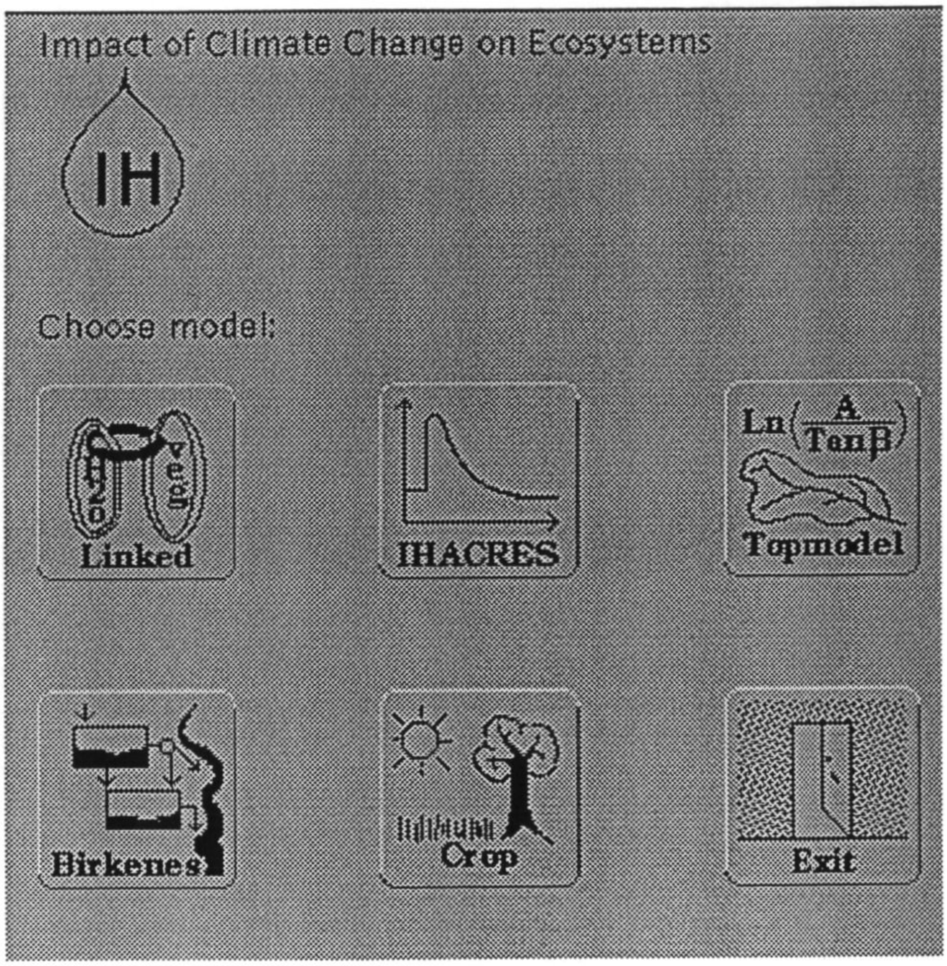
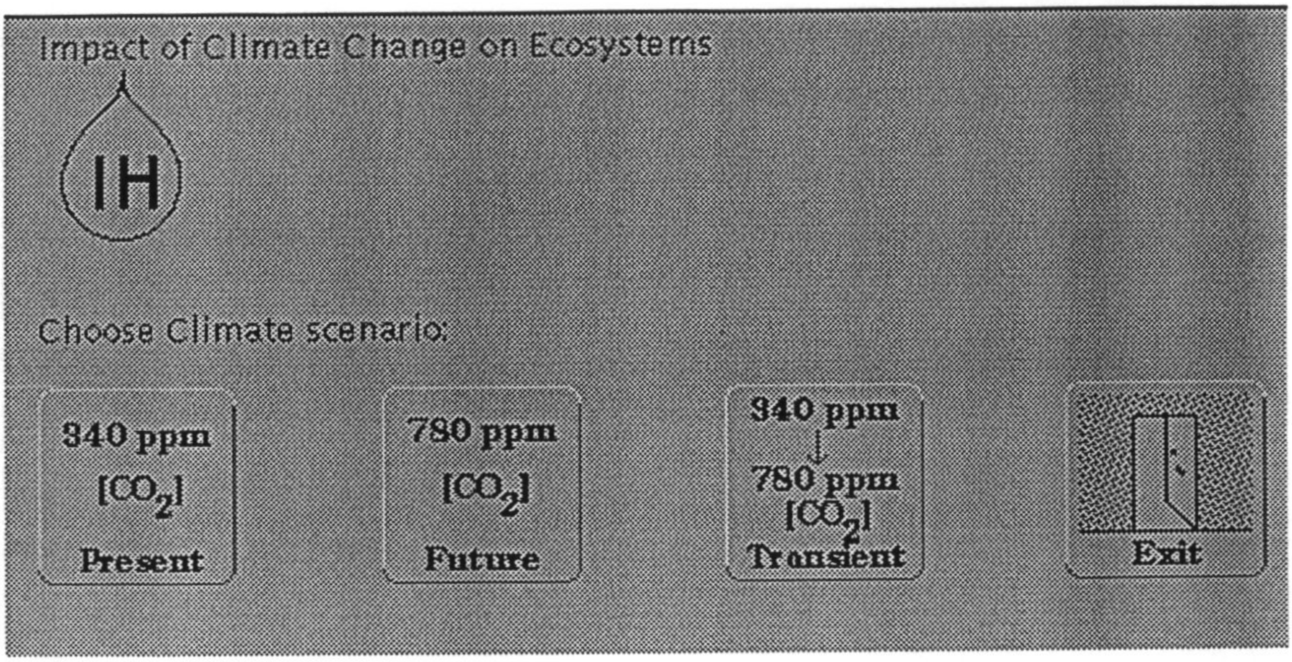

Impact of Climate Change on Ecosystems
IH
Choose model:
Linked
IHACRES
Ln(A/TanB)
Topmodel
Birkenes
Crop
Exit

Figure 34


Impact of Climate Change on Ecosystems
IH
Choose Climate scenario:
340 ppm
[CO2]
Present
780 ppm
[CO2]
Future
340 ppm
780 ppm
[CO2]
Transient
Exit

10.5) The select menu

The last option on the 'Start' menu displays the 'Select' menu (Figure 35), which can be used to choose a catchment or catchments on which the selected model will be applied. Selecting the 'One' option produces a map of the UK with the gauged catchments boundaries superimposed. A catchment can be selected using the displayed cross-hairs and once selected the screen is cleared and the catchment outline redrawn at a maximum scale for clarification. If the 'Many' option is chosen a number of catchments can be chosen. The 'All' option selects all of the UK catchments.

Using a combination of the 'Plot' and 'Select' buttons, details of individual catchments can be displayed. For example the Land use and river network could be displayed for a particular catchment.

10.6) Future developments of the Menu System

At present the 'Start' menu contains no 'Run' option. The 'Run' option will be incorporated to allow the user to run the selected climate scenario and model on the selected catchments. The AML behind the button will use the 'overlay' facilities of Arc/Info to select the data appropriate to the catchments selected by the user (and relate to an external database *e.g.* Oracle, if required), as well as the appropriate climate scenario. The data will then be passed to the model, selected by the user, and the model from the Arc/Info AML. Once completed the model will pass the results back to the GIS for display purposes.

The Institute of Hydrology is the repository for the UK Surface Water Archive (SWA), which consists of the flow records for the 1000 plus gauged UK catchments (Section 2). If the UK gauged catchments Arc/Info coverage dataset is identified by catchment ID then using the Oracle link it will be possible to pull the SWA data into the menu system for display and as data for the hydrological models. It is proposed to attempt this next year.

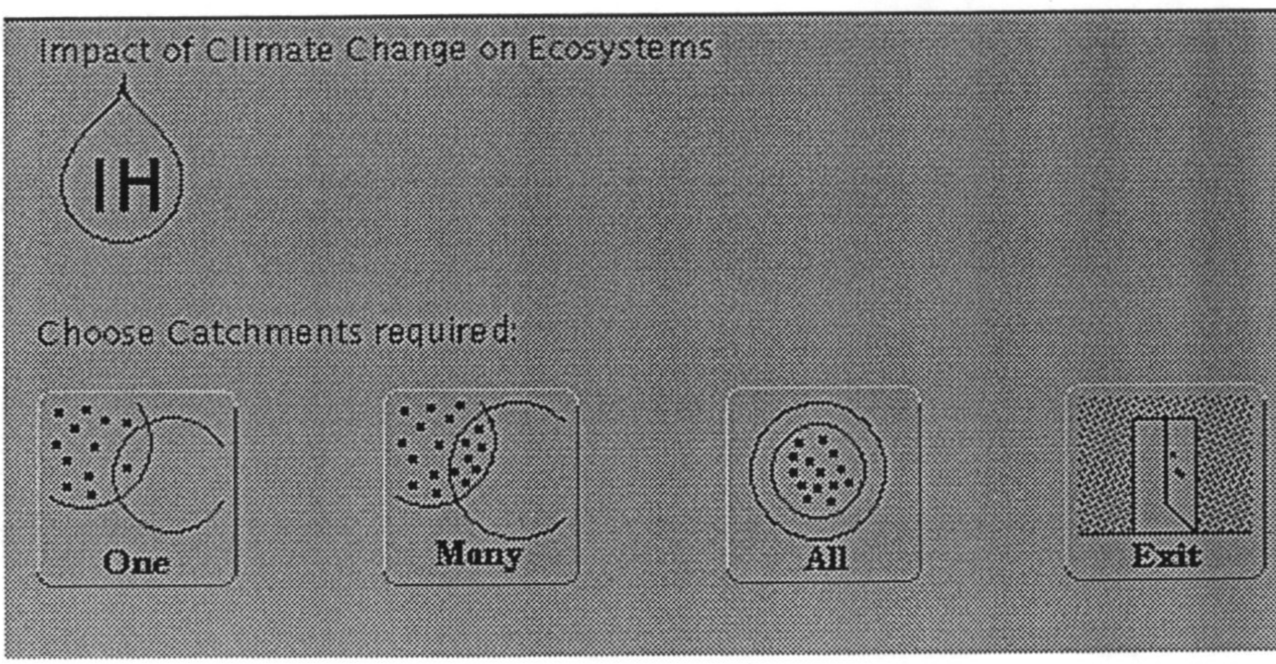
The Arc/Info (Version 6.1) Grid package has built in a number of hydrological features that could be of use to the Climate Change study. These include automatic generation of; flow direction, flow accumulation, calculation of sinks and catchment delineation all from a given grid format DTM. These function may assist in the regionalization aspects of the climate change project and these will be investigated and utilized appropriately.

11) TIGER IV project research

11.1) Objectives

a) To model the dynamics of catchment water balance components using national databases of rainfall and streamflow.

Figure 35



Impact of Climate Change on Ecosystems
IH
Choose Catchments required:
One
Many
All
Exit

b) To establish relationships between dynamic response characteristics (DRCs) derived from (a) and physical catchment descriptors (PCDs) databases held in a Geographical Information System (GIS) (topography, soils, land-use, etc.). Subsequent estimation of DRCs for ungauged catchments -- to cover the UK -- and derivation of a GIS-based hydrological model for the UK and (subject to data availability) Europe.

c) To apply specified climate change scenarios to the GIS hydrological model to assist with impact studies for the TIGER IV 3(a) consortium project "Landscape dynamics and climate change at national and European scales". The hydrological models will be used to drive soil chemistry models to provide information about nutrient status changes.

11.2) Relation to other work in the consortium project

Ecosystems and hydrological systems are inextricably linked. Changes in hydrological conditions will cause changes in ecological assemblages and vice versa. A well known example is the increase in catchment evapotranspiration due to closed-canopy coniferous forest. Conversely, if increased levels of atmospheric CO_2 cause stomata to open less it may lead to reduced transpiration losses from vegetation.

This sub-project will make available to the other participants in the project spatially distributed information throughout the UK on catchment wetness and runoff responses to (historic or scenario) changes in the driving variables of rainfall and temperature.

11.3) Research strategy

Of all the issues facing environmental scientists, it is that of environmental change that is perhaps most crucial. Of particular strategic importance is the extrapolation of assessment methods to a spatial scale so this regional and national pattern can be addressed.

Across the UK, Europe and North America environmental change networks have, or are being, established to monitor ecosystem response to changing climatic conditions. Such networks include:

a) The TFSD Ecosystems Change Network (ECN) (4 UK sites);
b) The DOE Acid Waters Monitoring Networks (20 UK sites);
c) The European Network of Catchments Organised for Research on Ecosystems (15 sites in 8 countries across Europe);
d) The US Geological Survey Benchmark Sites (50 sites across North America).

At present there are major methodological problems with identifying change in such systems because of the underlying complex dynamic processes controlling system behaviour and the inherent stochastic nature of the environment. There are few techniques capable to identifying temporal change and even fewer capable of being extrapolated across regions or countries to give a spatial picture of the hydrological impacts due to environmental change. Fundamental to understanding ecosystems change is a knowledge of underlying dynamic hydrological processes.

One approach that has been developed recently which provides a consistent and reliable technique for hydrological modelling on wide spectrum of catchments is that of IHACRES (Identification of unit Hydrographs And Components flows from Rainfall, Evapotranspiration and Streamflow data) (Jakeman *et al.*, 1990). IHACRES uses advanced statistical algorithms to compute underlying hydrological characteristics such as catchment response times and runoff volumes contributed by quick and slow flow processes. IHACRES has been applied to twenty five sites in the UK, North America, new Zealand, Australia and provides a well proven description of catchment response across a wide range of climates and landscapes.

Dynamic response characteristics (DRCs) identified by IHACRES will be related to physical catchment descriptors (PCDs) such as catchment slopes, topography, aspect, land use, soil type, soil depth, geology etc. If relationships between DRCs and PCDs can be established then a means of extrapolation on a regional or national basis is available by making use of the UK databases such as the ITE land use database, the IH Hydrology of Soil Types data base, the digitised river network database, the digital terrain maps etc.

IHACRES will be applied to at least 50 and more than 100 catchments and a comprehensive database of DRCs and PCDs established. Statistical techniques, such as multiple regression and principal components analysis etc., will be employed to establish relationships between DRCs and PCDs. These relationships will be used in conjunction with a GIS system on a SUN workstation to link UK national databases, such as HOST, land use etc., to provide DRCs across the country. This sill provide a GIS-based model with which to investigate hydrological response across the UK.

IHACRES has been applied to 25 sites already and the model gives an excellent fit to observed flow for two very different catchments (Kirkton in Scotland and Hafren in Wales). Typical dynamic response characteristics obtained from IHACRES include response time of slow flow (groundwater and deep soil water) component, response time of quick flow component (surface runoff and shallow soil zone) component and volumetric ratio of surface runoff to groundwater flows. Such DRCs appear to have a relationship with physical catchment characteristics. In addition theoretical simulations by Wollock *et al.* (1970) have shown that topographical characteristics will control the dynamic response of catchments.

Other related previous work includes the research of Hornberger *et al.* (1989), Whitehead *et al.* (1988) and jenkins *et al.* (1990) who have shown that hydrochemical models for individual sites can be related to regional behaviour. In particular the MAGIC model was used to model regional hydrology and water quality across Wales, Scotland and Norway. The output from the GIS-based hydrological model will feed into MAGIC to give improved models of soil nutrient status changes associated will climate and land-use perturbations.

Finally and most importantly databases are available on a landscape on such physical parameters as soil hydrology (HOST), land use, aspect, altitude, geology etc. These have been established on GIS systems at Monkswood and at Wallingford. In addition hydrological time series are available as part of the surface water archive at IH.

12) Future developments

In the final year of this project a number of objectives will be met. These are listed below along with any possible difficulties in meeting these objectives.

1) Further refinement, calibration and testing of the hydrological and hydrochemical sub-models available. This will include continued assessment of the Birkenes hydrochemical model and the IHACRES hydrological modelling scheme.

2) Development of a long-term vegetation model capable of simulating the growth of forest *etc.*

3) Construction of the fully linked model to incorporate vegetation, hydrology, nitrate and water/soil chemistry sub-modules and capable of simulating the impacts of climate change at an equilibrium time scale. The further development of the model to predict biogeochemical impacts over transitional time periods is likely to require further model development but will, as a minimum, be assessed for the final report.

4) Validation of the linked model. This will be initially carried out at the Balquhidder catchment where land use is constant and high quality data exist. Regional validation and application of the linked model will be dependent upon the availability of the detailed data required to run the model.

5) Development of the software to enable models to be run from the GIS menu system with full graphical results displays. This is ultimately dependent upon the availability of the object code licence for Arc/Info and the necessary documentation under the CHEST deal. However simple regression models such as the SMD model [11] will be incorporated into the AML of Arc/Info in the near future.

6) Establishment of the software links for accessing the Oracle database (with relational data for existing datasets) from the Arc/Info menu system. This is dependent upon the software and hardware links between the workstation where Arc/Info is being run and the database server on the Ethernet network where the Oracle database is situated. At present the link is not functioning.

7) Application of the linked model using regional and catchment based climate change scenarios. This is dependent upon the availability of both baseline and future predicted climate data. At present the source of baseline climatology data remains uncertain. One option is to utilise the limited amount of baseline data available at IH and extrapolate for missing data. In the near future modelled transient data should be available from CRU LINK, although the grid scale of that data (2.5° by 3.25°) would make disaggregation of individual catchment data problematic. Clearly, the generation of baseline climatology data from existing data sets and of future perturbed climate data from GCM output will be time consuming. It remains a to be decided as to whether this project should concentrate on model development or application.

This stage of the research programme also provides an opportune time to identify work which will require a longer time frame than the existing project. The most important aspects of impacts related work essential to the development of methodologies and not specifically directed at any impact related area include;

8) Incorporation of further vegetation and crop growth / yield models into the linked framework. This would enable a more realistic 'impact' assessment for the UK to be achieved.

9) Development, aquisition and validation of further UK, fine resolution datasets such as DTM and land use. High quality datasets will inevitably produce more reliable model output.

10) Validation of multiple linked sub-models at sites where climate is to be manipulated, for example the recently started CLIMEX experiment in S. Norway. The manipulation (increased [CO_2] and temperature) will begin in January 1994. Experiments of this sort will provide the only real validation of our models in the medium term future.

11) Detailed sensitivity analysis of the final linked model with respect to predicted climates, that is, what are the most important parameters for our models and are these available at an acceptable resolution. Rigorus sensitivity analysis on a model of the scale of the linked model would be a major tesk but will provide essential information to support future emissions negotiations.

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