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Spatial and temporal predictions of soil moisture patterns and evaporative losses using TOPMODEL and the GAS-FLUX model for an Alaskan catchment

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Abstract

By using topographic indices as derived from a Digital Terrain Models (DTM), it is possible to represent the heterogeneity within a landscape. This heterogeneity can reflect both long term evolutionary patterns seen in a landscape and the short term forcing of flow dynamics during storm events. By spatial analysis, the linkage between the geomorphological-hydrological-plant physiological phenomena can be examined. In this study, a direct link will be established between the topographically-driven hydrological phenomena and the eco-physiological response. The topographic distribution function of TOPMODEL is used to control the spatial and temporal flux of the channel flow and water table. The plant physiological model GAS-FLUX is used to give a spatially and temporally dissaggregated species-sensitive estimate of evapotranspiration flux. Evapotranspiration is sensitive to the vegetation phenology, to tundra community physiology and to the temperature regime. A simple linking of TOPMODEL and the GAS-FLUX model is applied to a summer snow-free period to the Imnavait catchment, Alaska (2.2 Km^2). A species-sensitive evapotranspiration model proved to give the highest quality results when validated against flow observations. Predicted dynamics of variable source area and the component hydrological processes are illustrated.

Introduction

The subjects of catchment hydrology and catchment eco-physiology have remained separate for many years. Hydrologists commonly use resistance terms to approximate plant transpiration dynamics (Monteith, 1965) and, typically, plants transpire in response to the meteorological conditions of temperature, humidity and radiation and not to the plant physiology. Components relating to the role of soil moisture and the physiological response of vegetation to water stress have not been addressed adequately by the hydrologist. Rather, catchments have been assumed to be spatially homogeneous with respect to vegetation structure and functions. Any dynamics in the evaporative component of the water balance come from atmospheric control only. Recent GCMs (General Circulation Models) that include plant physiological concepts have attempted to approximate the hydrological feedback control on plant resistance. Still, the SiB (Simple Biosphere model, Sellers *et al.*, 1986) or BATS (Biosphere Atmosphere Transfer Scheme, Dickenson and Kennedy, 1991) over-simplify the soil moisture term by using an areal average.

Jarvis (1986), Tenhunen *et al.*, (1990), Davies and Zhang (1991), Tardieu and Davies (1993) and Sala and Tenhunen (1994) have demonstrated the complex manner in which above and below ground factors control canopy conductance interactively. These eco-physiological studies see the soil moisture control predominantly in the sense of soil water limitation. In Alaska, however, water is not a limiting factor. Even during long interstorm periods over summer, water is available from permafrost melting and capillary rise (Hinzman *et al.*, 1995 and Tenhunen *et al.*, (1994)). The hydrology does, however, control the redistribution of nutrients within the system. Thus, even without water stress, the LAI (Leaf Area Index) distribution and the vegetation communities' phenology are dependent on hydrological/geomorphological factors (Ostendorf and Reynolds, 1995). The degree of saturation within the catchment is also spatially dynamic and controls hydro-ecological niches strongly. The implications of saturation to each vegetation community and to CO$_2$ flux and storage is important. Whilst this work has been carried out for the relatively undisturbed environment of Alaskan tundra, the implication for temperate zones remains high. The prevalent use of fertiliser and its transportation within the hydrological system can similarly influence the spatial variation in LAI development and evaporative fluxes in temperate ecosystems (for example in meadows and grassland).

Hence, the choice in this study is to determine the evapotranspiration flux in the landscape by using the ecophysiological GAS-FLUX model (Tenhunen *et al.,* 1989 and 1990). The model represents the structure of vegetation communities and provides mechanistic physiological functions that control gas exchange. The GAS-FLUX calculations are based on an extended period of field study (as reported in Tenhunen *et al.,* 1994). The model has been parameterised and applied in detail in tundra and the Mediterranean region (Tenhunen *et al.,* 1990 and Ostendorf *et al.,* 1993).

A hydrological model that could trace the evolution of soil moisture patterns in space and time is also required. The variability of the water availability around a catchment could be calculated using the model TOPMODEL (Beven and Kirkby, 1979, Beven *et al.,* 1996). The implications of catchment heterogeneity and soil moisture dynamics in controlling evaporative energy flux have already been discussed in Quinn *et al.,* (1995a) and Beven and Quinn, (1994).

The landscape is formed by the co-evolution of many processes; thus fieldwork and modelling should include consideration of the geomorphology, the hydrology and the plant ecology. The measurable properties of any catchment system, as seen today, must be an expression of all these processes acting interactively over time. Hence, this study develops a direct soil moisture-plant eco-physiology link. Topographical wetness indices (as determined by terrain analysis Quinn *et al.,* 1991 and Ostendorf and Reynolds, 1993) can be used to reflect the long term interaction of the geomorphology and the hydrology. An operational hydrological model, TOPMODEL, controls the soil moisture redistribution and the runoff for a given series of hydrological inputs, thus reflecting the short term dynamics of the system. Finally, the GAS-FLUX model, which is sensitive to the plant community, the phenology and the atmospheric conditions, gives rise to an estimate of the evapotranspiration losses. Similar attempts at improving the land surface representation and the plant evaporation dynamics have been reported by Famiglietti and Wood (1990) which uses a variant of the topographic index approach followed here. An extension of this work, which examines the consequences of spatial variation in water table for tundra CO_2 exchange and storage, is fully reported by Ostendorf *et al.,* (1995).

The Imnavait Creek catchment

Imnavait Creek catchment (Fig. 1) covers about 2.2 km^2 with an elevation range from 877 to 961 m, in the rolling hills north of the Brooks Range in Northern Alaska

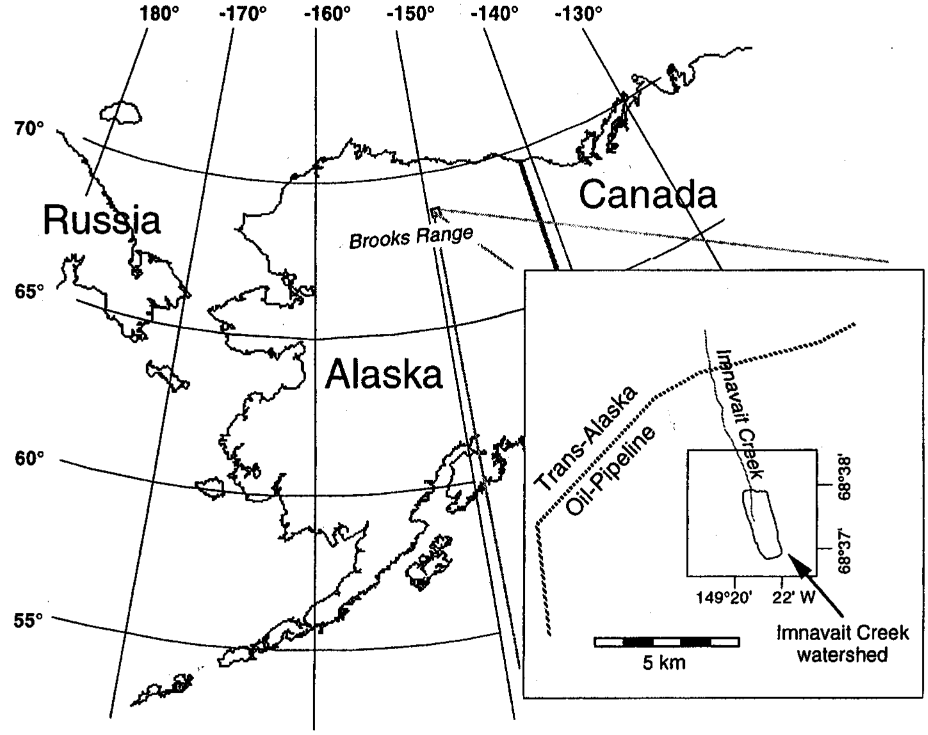

Fig. 1. *The location of the Imnavait Creek study area in Alaska.*

(68°37′N, 149°20′W). The location of the study site is approximately 200 km south of the northern Alaska shoreline. The low slopes of the catchment (average of 7%) differ from many TOPMODEL applications where the topography has been steeper. The catchment has not been glaciated since the Pleistocene and remains largely undisturbed by human impact. Thus, the current vegetation reflects the long-term interactions of vegetation and soils development with the hydrological regime. It is generally thought that TOPMODEL works better in steeper topography and in wetter climates where near surface active hydrology is dominant. TOPMODEL assumptions seem to apply here due to the solid surface of permafrost which defines a shallow hydrologically active zone.

Vegetation and soils in the study site have been described in detail by Walker *et al.*, (1989). The area of permafrost has a maximum depth of less than 1 m. Typically snowmelt occurs in early June with the possibility of snow storm events at any time of the year. At Imnavait Creek precipitation during the snow free period between 1986 and 1990 ranged from 90 to 260 mm. The vegetation patterns follow topographic gradients of water availability. The differences of the vegetation are mainly due to a shift in species composition rather than in distinct communities (Walker *et al.* 1995 and Hahn *et al.* 1995).

Three vegetation community classifications will be used in this study: dry shrubs (ridge tops), tussock tundra (mid slopes) and wet meadow (riparian area). Dry shrub vegetation (on ridge areas) is characterised by a higher proportion of evergreen shrubs; tussock tundra (mid-slopes) is dominated by *E. vaginatum*. Graminoid species occur with a higher frequency in the riparian wet meadows. Slopes with *E. vaginatum* tussocks have low LAI. Riparian meadows have the highest LAI in deciduous shrubs and graminoid species (primarily sedges) and lack representation by evergreen shrubs. Numerous ephemeral channels, referred to as 'water tracks' cut across the hillslope (Everett and Ostendorf, 1988). Whilst these exist, they do not characterise the slopes and have not been considered. The strong relationships between vegetation and the hydrological regime were quantified in a predictive model of vegetation types based on topography (Ostendorf and Reynolds, 1995). The computed vegetation map compared favourably in accuracy with the results of a classification based on satellite imagery at the same area (Stow *et al.*, 1989). The NDVI (Normalised Difference Vegetation Index) as derived from a satellite scene was found to be correlated with a runoff index pattern computed in a similar way as the topographic index used in TOPMODEL (Ostendorf and Reynolds, 1993). These studies indicated that TOPMODEL should be applicable to this system in spite of the shallow topography and the relatively low precipitation rates.

The period simulated with TOPMODEL in this study is restricted to a summer, snow free period with an emphasis on simulating the biologically active season. Snowmelt events of the catchment have been modelled in detail by Hinzman and Kane (1991). For rainfall/runoff simulation only the 1986 dataset proved to be of sufficient quality for modelling. The later years through to 1990 showed clear problems with the runoff measurements. It is thought that the automatic flow gauges (operated after 1986) were not capturing the low flows due to flow under the gauge, a feature that is easily seen on the flow hydrographs. A simple correction for flow losses could not be made (discussed in Hinzman *et al.*, 1995).

TOPMODEL and Digital Terrain Analysis (DTA)

TOPMODEL (Beven and Kirkby, 1979) is used for the functional representation of catchment hydrological processes that may be related to geomorphic form. With the wide availability of Digital Terrain Models (DTMs), terrain analysis has become a powerful tool within many applications (Beven and Moore,1993). TOPMODEL has been applied to soil moisture mapping, geochemical fluxes, evapotranspiration, erosion and sedimentation. Examples for a range of locations can be found in:– Beven *et al.*, (1984); Hornberger *et al.*, (1985); Beven (1986); Wood *et al.*, (1988); Famiglietti and Wood (1991); Robson *et al.*, (1992); Quinn and Beven (1993) and Quinn *et al.*, (1995). More recently a detailed review of TOPMODEL and terrain analysis can be seen in Beven *et al.*, (1996) and Quinn and Anthony, (1998).

In this application four parameters were required for calibration in order to simulate the observed field data:–

m (m) : is the exponential rate of decline of soil transmissivity with increasing soil depth.

T_0 (m^2/hour) the lateral transmissivity of the soil profile when the water table just intersects the surface. The logarithmic form arises from an assumption that the transmissivity of the soil falls off with depth (Beven, 1986).

SRMAX (m): The maximum depth of water that can be stored in the root zone, so that evaporation will cease when the store is depleted and unsaturated flow to the water table will commence only after the root zone capacity has been exceeded.

CHV (m/hour): The channel routing velocity.

Digital terrain analysis in hydrology was concentrated initially on direct morphometry, for instance the estimation of catchment size, boundary positions and river delineation (Band 1986, Morris and Herdeegen 1988, Tarboton *et al.*, 1991). A different modelling approach has emerged informed by research into the dynamics of variable source areas (Hewlett and Hibbert, 1963, Dunne and Black 1970, Sklash and Farvolden 1979). The significance of catchment topography in controlling the spatial pattern of stormflow source areas was recognised by Hewlett and

Troendle (1975) who suggested a relationship between slope contours and the likely distribution of source areas. Subsequently, TOPMODEL was developed, based on a group of concepts which may be construed as an interface between basin topography and flow patterns in time and space. TOPMODEL utilises a topographic index which represents a theoretical estimation of the accumulation of flow at any point. The distribution of the index may be calculated for any catchment and is used as a basis for the prediction of source areas, saturation excess overland flow and subsurface flows. TOPMODEL can be used to predict both hydrographs and a distributed water table. Water table depths may be predicted for any DTM pixel within a catchment. Modification of the local water table depth by capillary fringe effects, by evapotranspiration through a root zone and by recharge through an unsaturated zone store gives an estimate of local soil moisture status. Calculated local water table depths depend on the value of a topographic index or 'wetness' index at a point.

The index has the form:

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

where, in terms of a raster DTM:

a the upslope area, per unit contour length, contributing flow to a pixel;

tan β the local slope angle acting on a cell; this is taken to approximate the local hydraulic gradient under steady state conditions.

Figure 2, shows the Imnavait Creek catchment with a superimposed $ln\ (a/tan\ \beta)$ pattern. By analysing the pattern of the values seen in Fig. 2, a distribution function of the observed values can be produced (as can be seen in Fig. 3, which has a $ln\ (a/tan\ \beta)$ increment range of 0.5).

An alternative expression is the combined soils/topographic index, which is the form used in this application:

$$ln\ (a\ /T_0\ tan\ \beta)$$

TOPMODEL works through the use of simple distribution empirical functions. The distribution function relating the $ln\ (a/tan\ \beta)$ index to fractional areas of the catchment is of primary concern in this paper. When expressed as a combined soils/topographic index, the transmissivity parameter T_0 is commonly taken to be a constant, lumped catchment parameter. This has a simple scaling effect on the topographic distribution function. Should spatial soil data be available, or an obvious pattern in catchment soil characteristics exist, then a spatially-distributed T_0 may be used and included in the terrain analysis procedures for calculating $ln\ (a/T_0\ tan\ \beta)$. In this paper, however, it will be assumed that T_0 is constant in space. The main concern in this study is the effect of topography on patterns of likely water accumulation within the catchment.

The first such automated DTA procedure for the index calculation was reported by Quinn *et al.*, (1991). This form of DTA makes it very convenient to calculate the distributed topographic index for any catchment, given a suitable DTM. It is therefore unsurprising that the topographic index $ln\ (a/tan\ \beta)$ has been used frequently to visualise macroscale flow patterns within catchments.

In TOPMODEL applications, a good quality DTM is

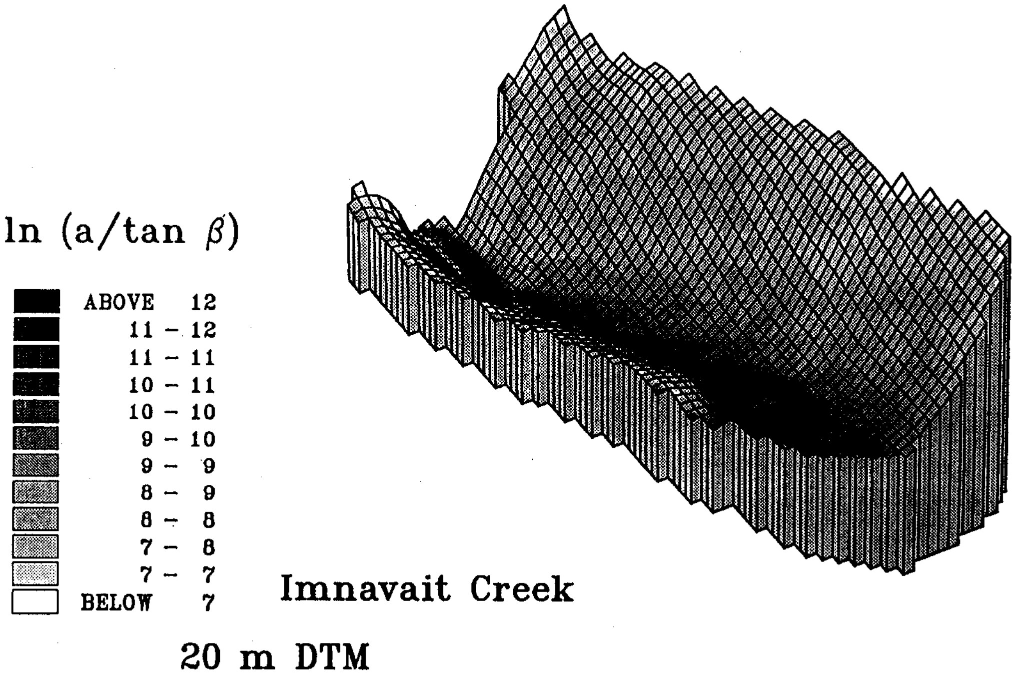

Fig. 2. *The Imnavait Creek catchment, a 20 m resolution DTM with the superimposed* $ln\ (a/tan\ \beta)$ *index values.*

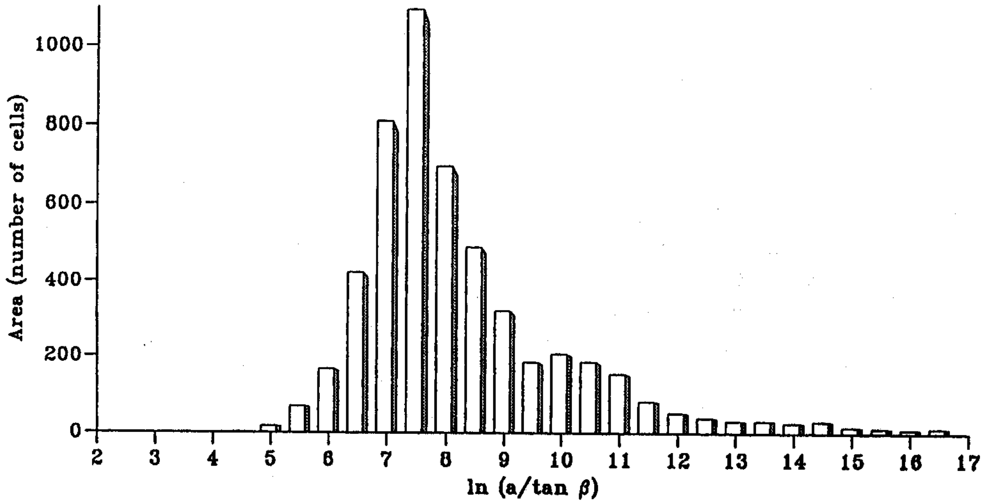

Fig. 3. *The ln (a/tan β) index function for the information in Fig. 2.*

required, so that downslope flow pathways can be determined with a degree of accuracy. There then follow two components to the DTA, the first is in the derivation of the *ln (a/tan β)* index, a representation of the likely position of the water table. The second is the process of subcatchment derivation and channel delineation, which together control the channel flow routing of TOPMODEL. The issues relating to the calculation of the index and its use within TOPMODEL are thoroughly reviewed in Quinn *et al.*, (1995b).

Figure 4, shows all the spatial datasets used in the paper. A common grid size of 20 m was used for all the analysis (as in Fig. 2, the DTM grid resolution). The final vegetation classification (Fig. 4a) represents the three vegetation communities used in the full GAS-FLUX simulation exercise.

The LAI (Leaf Area Index), Fig 4b, is a commonly used vegetation attribute often used in land classification schemes. The LAI pattern does match some aspects of the topographic index and the vegetation communities. However, a classification alone on LAI is not as representative as the vegetation community classification. Classification schemes based on LAI and NDVI alone may miss the importance of the vegetation community structure.

In Fig. 4c, is the pattern of the topographic 'wetness' index *ln (a/tan β)*. A clear match is seen between the vegetation class and the topographic index. To link TOPMODEL and the GAS-FLUX patterns, the strong correlation of the vegetation pattern and hydrological conditions at the site is employed (Ostendorf and Reynolds, 1993). Using two *ln (a/tan β)* thresholds, the vegetation map could be generated with an accuracy of 73% (Ostendorf *et al.*, 1995). Thus, without major modifications, TOPMODEL can directly use transpiration estimates from the GAS-FLUX model. The optimum thresholds values used within the TOPMODEL distribution were 7 and 9. The implication to the classification methodology is that a larger catchment area, without the detailed vegetation classification, could be defined on the topographic wetness index alone. The closeness of the fit reflects the fact that the system has co-evolved both in terms of the geomorphological-hydrological link but also in the hydrological-eco-physiological link.

Figure 4d, is a map of the distance to the outfall for a series of time delay isochrones. Once the likely channel routing velocity (this is the CHV parameter of TOPMODEL) is assessed, an estimate of the number of discrete isochrones needed to route the flow to the outfall can be made. A channel can be defined for the catchment using a simple area threshold to state the locations of channel initiation. These initial cells are then cascaded to the outfall to trace the path of the channel. A series of time delay isochrones 'bands' can be defined (500 m increments were found to be suitable for this application). The area that drains through each 500 m increment band can then be determined and quantified.

The GAS-FLUX model

A detailed eco-physiological model (GAS-FLUX, Tenhunen *et al.*, 1990) has been parameterised for three vegetation classes of Imnavait Creek (Tenhunen *et al.*, 1994). This model represents a mechanistic framework for integrating knowledge of tundra gas exchange. GAS-FLUX considers the vertical structure and microclimate of a vegetation community which is assumed to be homogeneous. The vascular plant canopy is divided into a series of layers containing leaf and stem information, each with a defined species-sensitive physiological response (as determined from field measurements). Vascular plant biomass is distributed among three functional physiological

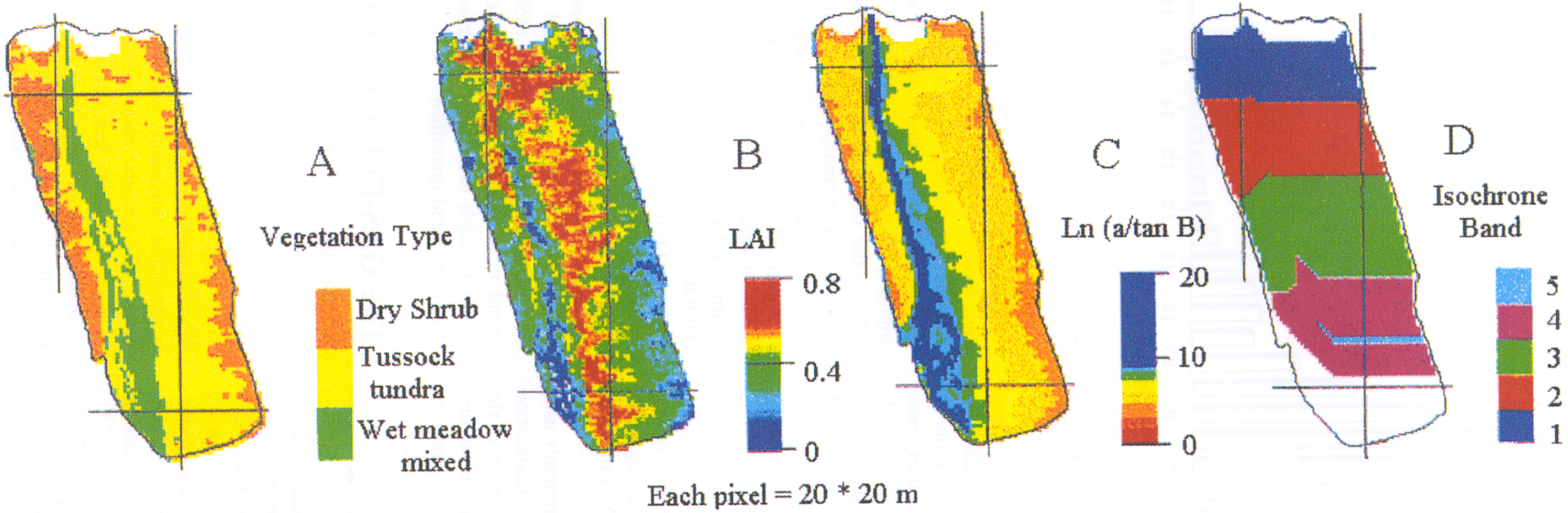

Fig. 4. *Spatial data used in the analysis a) vegetation classification, b) LAI Leaf Area Index map, c) the topographic index map, ln (a/ tan* β*), d) a map of time delay isochrones representing distance from the outfall.*

types; deciduous shrubs, graminoids and evergreen shrubs. Deciduous shrubs and graminoids occur in significant quantities in all three vegetation community classes, with the lowest LAI in tussock tundra and highest in the wet meadow zone. The stem area index of the deciduous shrub plays a role in light interception in all three communities, but decreases in the wet meadow zone due to rapid moss growth. Evergreen shrubs are equally present in the dry shrub and the tussock tundra community, but disappear in the wet meadow zone.

Light interception by both stems and leaves is considered. Light incident on the moss 'understorey' is that passing through the lowest layer of the vascular plant canopy. Just as sunlit and shaded leaf areas are calculated in each canopy layer, sunlit and shaded portions of the ground surface are also calculated. Photosynthetic response at the individual level of vascular plants of the three growth forms is described with the equations proposed by Farquar *et al.*, (1980). CO_2 assimilation is used in an empirical model to estimate stomatal conductance (Ball *et al.*, 1987). A constant transfer resistance is assumed from the moss surface to the air adjacent to the ground (1 to 2 cm above the moss) based on cuvette measurements. Average layer exchange rates for both vascular plants and moss are obtained by weighting the sunlit and shaded area fluxes. The low stature of the tundra communities and the limited depth to the permafrost provide advantages for model validation by chamber measurements.

Tenhunen *et al.*, (1994) analysed the behaviour of the three representative vegetation types on 5 different days throughout the season. The parameterisation includes the phenological state of leaf area index and differences in photosynthetic response of the plants over the season, as well as the structural information for typical dry shrub, tussock tundra and riparian wet meadow communities (Fig. 4a). The model was set up to evaluate the daily rates of CO_2 and vapour exchange for several different microclimatic data sets at 5 seasonal times (June 15, 30, July 15, 30 and August 15, 1985). The model response showed that the phenological status and diurnal radiation input proved to be of most importance in determining of diurnal rates of net CO_2 fixation (Tenhunen *et al.*, 1994)

Since feedback is not postulated between the hydrology and gas exchange regulation of the evapotranspiration, the response of each community was calculated *a priori* for the simulation period. Essentially the estimates of GASFLUX model will be accepted as a 'true' boundary condition for evapotranspiration losses. When the simulation results were analysed, it was seen that evaporation rates from the three vegetation classes were dependent primarily on phenology and on the daily average temperature. Thus, the complex response of the model could be simplified as a three dimensional response surface with axes of temperature and day of the year (Fig. 5) for the three vegetation types. Figure 5 shows the evapotranspiration response surfaces of riparian wet meadow (bottom), tussock tundra (middle) and dry shrub (top) vegetation as a function of phenological state and average daily temperature. The resulting seasonal time course of transpiration rates of two of the vegetation types is shown in Fig. 6. It can be seen from Fig. 5, that the dry shrub class and the tussock tundra class have a very similar response surface and have a similar time series but the cumulative evaporation can be quite different.

Imnavait Creek is also a 'water unlimited' catchment, water is supplied constantly, initially from melting snow

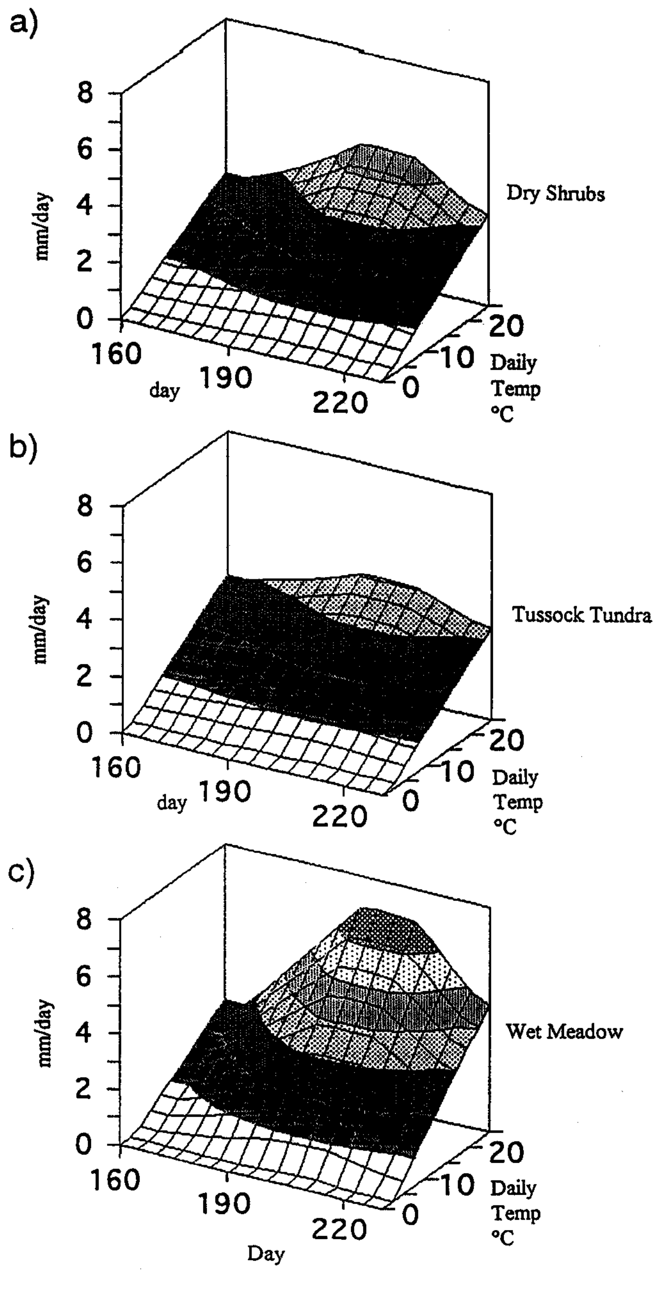

Fig. 5. *The evaporative response surface for the 3 vegetation types found within the catchment as controlled by the phenology (the day of the year since January 1st) and the daily average temperature.*

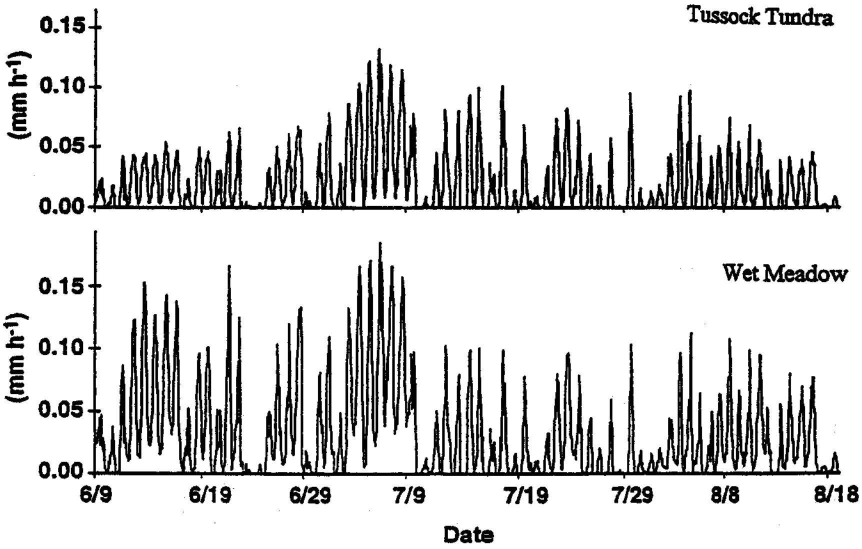

Fig. 6. *The evaporation for two of the vegetation types as produced by the GAS-FLUX model.*

and then from the melting of the permafrost, to the vegetation. Hence, it is assumed that there would not be extreme water shortage, as Ostendorf *et al.*, (1995) have pointed out. A simple formulation was thus chosen that allowed evaporation at the rate specified as by the GAS-FLUX algorithm. The evaporation would occur at full rate until the root zone was dry and evaporation would then stop. In essence, the total soil moisture available to the roots is modelled as a single root zone store (with an upper limit of SRMAX the root zone parameter). So an assumption that the root zone was large would cause the model evaporation to be the same as the GAS-FLUX model calculations.

Optimisation

For the current simulation, the '*m*' parameter was determined by recession analysis. Interactive calibration to a 'best fit' model is done by altering the parameters of SRMAX T_0 and CHV. A high level of model accuracy can be achieved in a short time period through interactive optimisation (aided largely by the fast run time of the model). Analysis showed that the CHV value could be quickly optimised in order to give a good time to peak for the flow and T_0 was rather insensitive. The goodness of fit criterion used here is based on a simple modelling efficiency calculation:–

$$E = 1 - (\text{variance of the residuals/variance of the observations})$$

Simple lumped evaporation TOPMODEL simulation

A first simulation of TOPMODEL was made to discover the dynamics of the model. In the first instance, a lumped evapotranspiration GAS-FLUX estimate was used. As the tussock tundra class was the dominant class by area (with very similar evaporative flux rates to the dry shrubs), this series of values was used to represent the total evaporative flux (from Fig. 6). An estimate of the parameter '*m*' was made by studying the recession curves. The T_0 value was set high (essentially suppressing large amounts of excess flow) and the channel routing value (CHV) was estimated by inspecting the timing of the observed and predicted flow peaks. In the first instance the SRMAX value was set high; therefore the total evaporation would be the same as the input value.

The parameter values chosen were:–

Parameter	m	T_0	SRMAX	CHV
units	m	m^2/hour	m	m/hour
value	0.02	2000	0.1	200

A simulation efficiency value of 78% was achieved for which the runoff dynamics can be seen in Fig. 7. The 1986 summer period was characterised by an initial period of snowmelt followed by a long drying period. Despite a number of storm events during the summer, there was no runoff. Eventually a series of large storms caused a significant runoff response in the two hydrographs seen. The period studied is a useful test for TOPMODEL as there are two large storm events to fit the hydrographs and also a long interstorm period that aids in the study of the evaporative drying before the storms. The results of the simulation show two weaknesses: the initial peak of the first storm has been largely missed by TOPMODEL, which suggests a weakness in the TOPMODEL evaporation procedure and the two main peaks are overpredicted suggesting a water balance problem during this period (again a possible evapotranspiration problem).

Any improvement on this simulation would require an

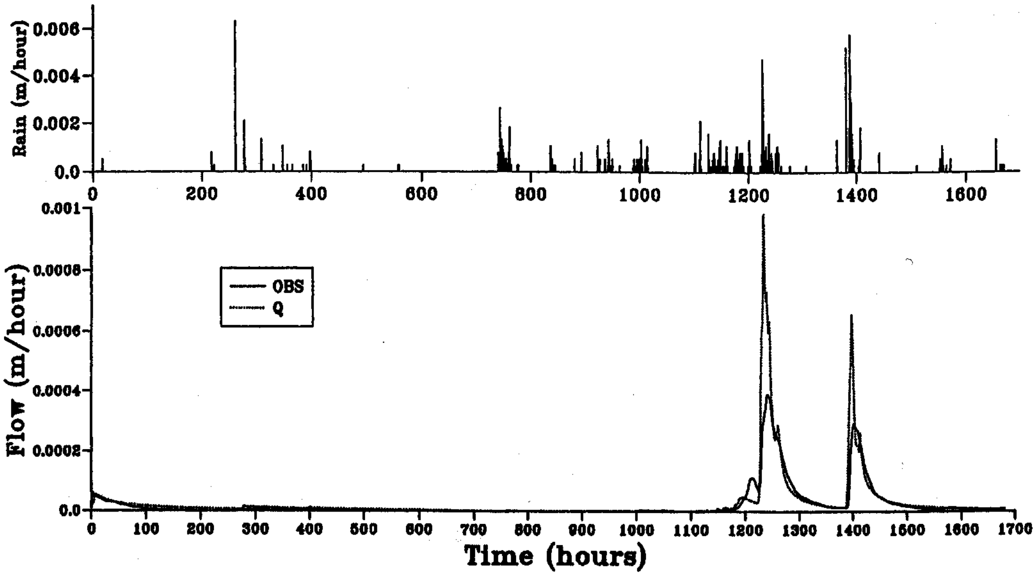

Fig. 7. *Rainfall runoff dynamics as produced without calibration and without a SRMAX root zone control (78% efficiency).*

increase in the losses from the flow. The options available would have been to increase the evaporative demand or apply a correction factor to the rainfall or runoff (assuming measurement error). The final disaggregated evaporation (shown below) reveals that the areal average of evaporation used in this simulation was too low to account for the remaining water in the budget.

Disaggregated evaporated simulation

Given the opportunity to disaggregate the evaporation term due to the observed direct link between topography and the plant physiology, a final simulation was made. The catchment was split into the areas based on the topographic index pattern (with index threshold values of 7 and 9). As TOPMODEL loops through the $ln\ (a/tan\ \beta)$ index calculations, the current vegetation class is known. Three input evaporation files (calculated by GAS-FLUX) were now read in for the wet meadow, tussock tundra and dry shrubs and used as the evaporation rate from the root zone of each vegetation class. This disaggregated TOPMODEL-GAS-FLUX model was now optimised interactively.

The final effficiency of the model was 92% (the hydrographs for this period are shown in Fig. 8). This much improved simulation quality results directly from the dissaggregation of the evaporation. The increase in evaporation caused by the wet meadow class has greatly improved the model. The timing of the increase in evaporation from the wet meadow may also be important as the model now predicts spatially variable antecedent root zone conditions before the rainfall events. The assumption of the earlier simulation that the tussock tundra evaporation value represents the total catchment was inadequate, even though it is representative of the greater part of the catchment. There is, in fact, insufficient evaporative demand within the model if only the tussock tundra evaporative demand is used.

The final parameters were:–

m	T_0	SRMAX	CHV
m	m^2/hour	m	m/hour
0.026	2000	0.020	200

The root zone storage (SRMAX) has gone to a smaller effective value. The disaggregated version has increased the total evaporation in the simulation and has, thus, cured the overprediction anomaly seen in the lumped situation. However, the occurrence of a lower effective SRMAX value now reflects the fact that there is now too much evaporation within the model. The lower SRMAX value affected only the wet meadow class and did not alter the evaporative flux of the other two classes by any major amount. The wet meadow evaporation changed from 159 mm as calculated by GAS-FLUX to 138 mm, as there are periods in the simulation when the meadow mosses' root zone was dried out completely. The drying out of the wet meadow, given its propensity to saturation, and the capillary rise of local soil moisture reflects an anomaly in the model and is not realistic. SRMAX is optimising to a lower value within the model in order to create the correct water balance for the runoff periods. This suggests that the GAS-FLUX evaporative estimates are generally too high. This causes the root zone to be too dry before the start of the major events thus suppressing runoff and lowering the model efficiency. The first peak of the major storm event is still missing due to the SRMAX value being slightly

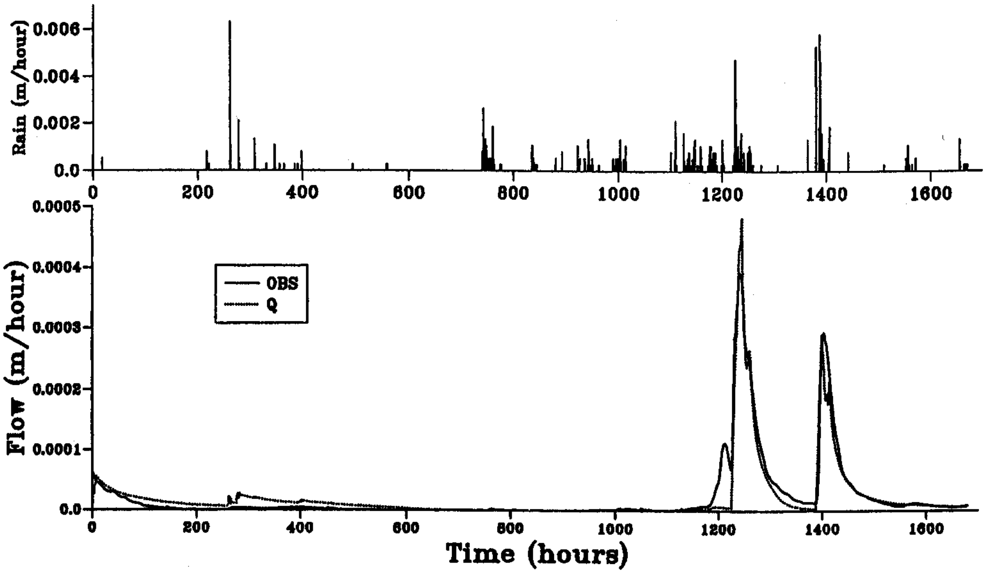

Fig. 8. *The best fit hydrographs as produced by the disaggregated evaporation model (92% efficiency).*

unrepresentative of the whole catchment. A correction to the *a priori* GAS-FLUX estimates is required to resolve this problem.

Benefits are seen by using a spatial and temporal evaporation routine that depends on plant physiological criteria. Parametric manipulation of the evaporation input data, although necessary, has been minimal. The dynamic fluxes of streamflow and evaporation have been well represented. A satisfactory operating model has been simulated but only for two storm runoff events. This lack of validation data may mean that the parameters may not be fully representative. A full validation of the model to a long series of good quality rainfall-runoff data is still needed.

Component processes

If it is accepted that the model is working to a sufficient degree of accuracy, an analysis of the component processes can be made to assess how the hydrographs are constructed. Essentially the power of the model is presented here, that is, all components of the model, both spatial and temporal, can be visualised and evaluated critically. The first factor is the overall water balance:–

Rainfall	Actual Evaporation	Subsurface Flow	Saturation excess flow
0.154 m	0.103 m	0.0344 m	0.0021 m

Evaporation losses dominate the water balance, thus demonstrating the importance of modelling this component as accurately as possible. Nearly all the flow generated is by the subsurface flow mechanism. Only 6.1% of the total flow is made up of saturation excess. The dominance of subsurface flow comes from the optimised *'m'* value which is small, hence nearly all the flow in the hydrograph is produced by subsurface flow. This makes the T_0 value rather insensitive and any large value will suitably suppress the saturation excess mechanism. The small *'m'* value gives a shallow but very active water table.

The aggregate evaporation was 121.8 mm over the 1680 hours of the simulation and was made up of:–

	GAS-FLUX input file	TOPMODEL using SRMAX= 20 mm
wet meadow:–	159	138 mm
tussock tundra:–	112	112 mm
dry shrubs:–	121	119 mm

The dynamics of all the TOPMODEL variables can be seen in detail (the most significant of which can be seen in Fig. 9). The evaporative demand and its corresponding effect on the root zone can be visualised. The root zone shown is that of the dry shrub vegetation area and it can be seen that with the optimum root zone size of SRMAX = 20 mm the root store zone was only empty for a few hours. The dynamics of the root zone status are very sensitive to the rainfall intensity and the magnitude of the GAS-FLUX evaporative estimates.

Also in Fig. 9, is the primary variable of TOPMODEL the *S* value (the mean soil moisture deficit) which controls the overall wetness of the catchment. The long summer dry period is matched by the steady increase in *S* (in an exponential form), followed by rapid changes in value after the root zone has filled and overflowed. The rapid change in the value of *S* is matched by a rapid change in the water table depth. The root zone status reveals a rapid evapotranspiration loss before the second storm commences, thus showing the importance to the storm runoff peak and the subsequent recession. The flow in the lower graph is

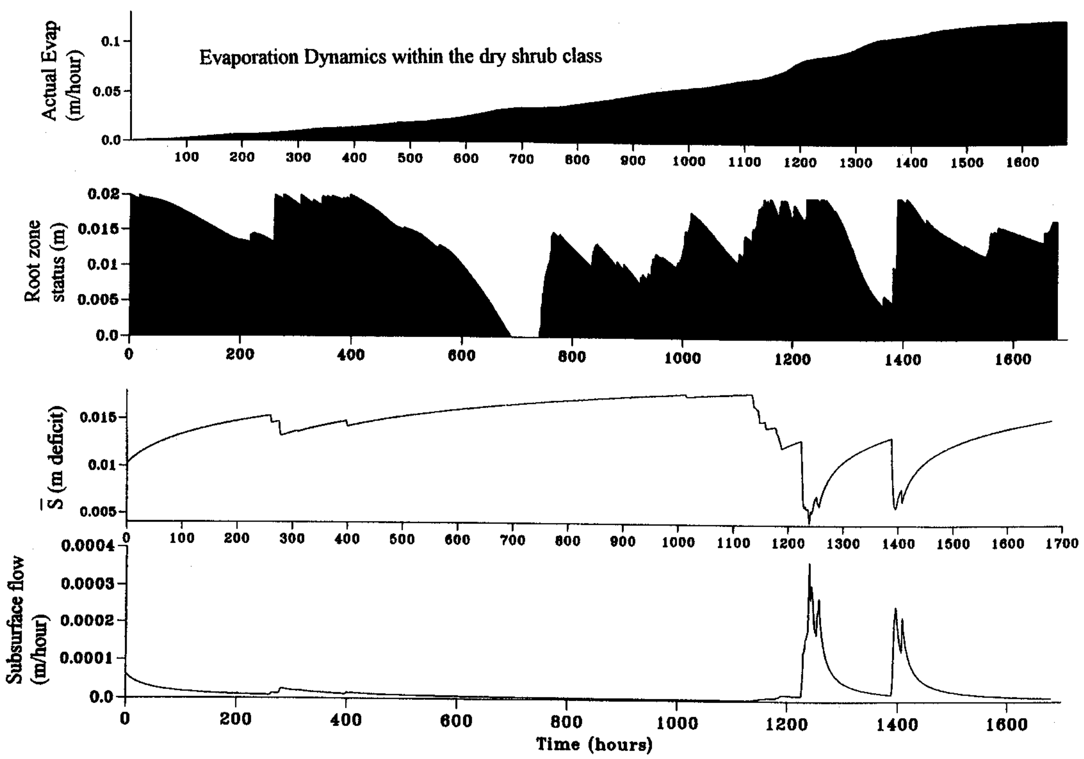

Fig. 9. *The component processes of TOPMODEL a) cumulative evaporation, b) the status of the root zone in the dry shrubs class, c) the fluctuation of the state variable S and d) the subsurface flow from the first isochrone band.*

the subsurface flow from isochrone band number 1, which is the mirror image of the *S* value.

Soil moisture dynamics

TOPMODEL allows for the calculation of the local water depth value (expressed as the local soil moisture deficit) whether for the whole *ln (a/tan β)* index increment or for a single grid pixel on the DTM. Given an optimum parameter set and a *ln (a/tan β)* index distribution, a map of the soil moisture deficit as predicted by TOPMODEL can be made for individual timesteps or accumulated over time to reveal the variable source area dynamics.

The first mapping option is to produce a soil moisture deficit map for an individual timestep. Figure 10, shows the soil moisture map for the driest hour observed across the simulation period. The power of this mapping procedure lies in the possibility of validating the pattern against some internal field measurements. The upper values of the soil moisture deficit imply a shallow active area of water table movement.

The dynamics of the variable source area can be described further by producing a cumulative frequency of saturation map. This is achieved by counting the number of hours that a cell is saturated and writing the final information back to the map. Figure 11 shows the dynamic of the saturated area, which reveals the permanently satu-

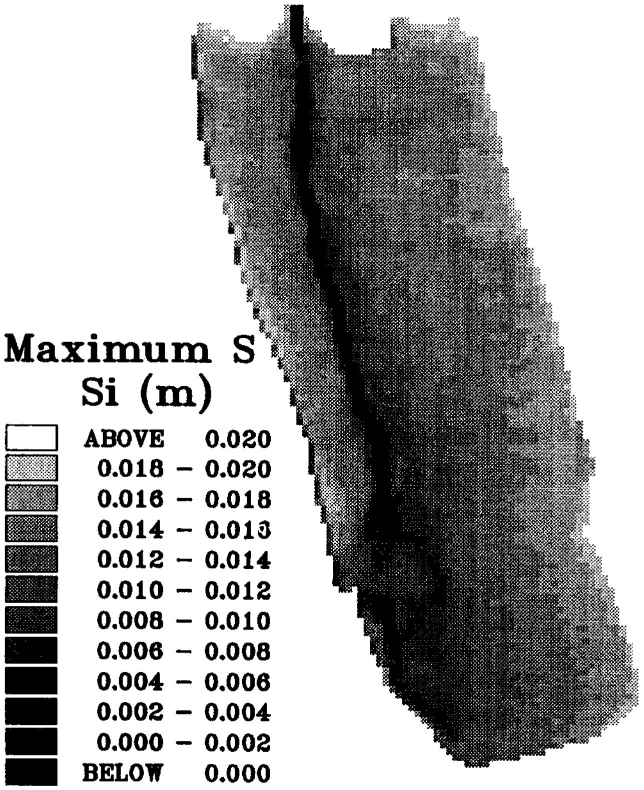

Fig. 10. *A map of the minimum saturated area for the modelled period (the largest S value).*

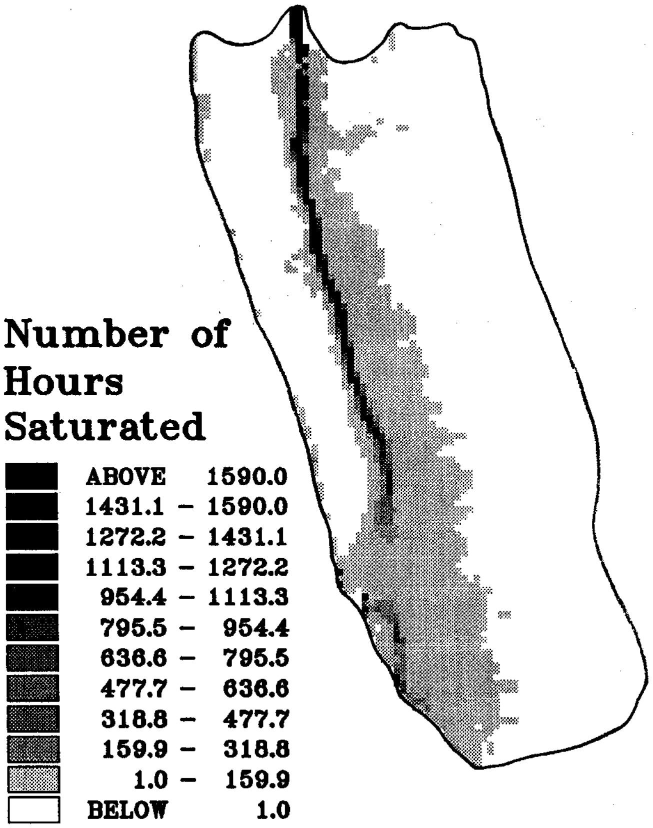

Fig. 11. *The cumulative frequency of saturation for each cell within the map, total duration of 1680 hourly timesteps.*

rated area and the ephemeral saturated area. This too reflects the hydro-ecological niche depicted by the wet meadow vegetation class.

Conclusion

A strong topographic-hydrological-plant physiological link has been shown, despite the low topography of the catchment. Imnavait Creek is a useful addition to the range of locations where TOPMODEL has been applied. DTA and the *ln (a/tan β)* index have proved a useful way of representing the heterogeneity of the system. DTA has aided the flow routing component by isochrone band delineation, which proved necessary due to the low CHV parameter value.

The GAS-FLUX has estimated the short term flux of evapotranspiration as controlled by the vegetation type, the phenology of the vegetation and the sensitivity of the vegetation to environmental factors (primarily temperature).

TOPMODEL represents the rainfall-runoff dynamics to a high degree of accuracy. The primary flow process is subsurface stormflow; this process is dominated by the correct evaluation of S per unit time. Runoff dynamics is subject to the antecedent conditions of the root zone, hence is sensitive to the evaporation estimates. During rain storms, the root zone antecedent conditions were very important, in many cases absorbing and suppressing the runoff. SRMAX was used to optimise the aggregate GAS-FLUX evaporation for the catchment (TOPMODEL can reduce an evaporative estimate if it is too high but can not increase evaporation if the estimate is too low). This suggests that estimates of the GAS-FLUX model may be in error; however, in the circumstances, the overall water balance and simulations are of good quality and inclusion of the spatial distribution of the vegetation communities has improved model accuracy. The best fit for TOPMODEL was achieved using the disaggregated evaporation option. Using thresholds on the *ln (a/tan β)* index, creates the class of vegetation to be used for reading in the separate input evaporation file as generated by the GAS-FLUX model.

In the final model the optimised parameters reflected the shallow but very active water table. The soil moisture dynamics are also shown in time and space. Subsurface flow in the near surface of the soil is predicted as being the dominant process of flow generation.

Both the hydrological and the plant physiological teams have benefited by combining their models and have shown an ability to run reasonable physically-based simulations at the catchment scale. The implications of such a model structure is great for land surface flux calculations and the automatic determination of antecedent conditions for the runoff scenario. Both the long and short term landscape flux in this study have revealed the linkage between the topography, the hydrology and the plant eco-physiology. In general, however, the model continues to have weaknesses; that, basically, a reliance on an accurate estimate of the overall evaporation rate per unit time and a longer times series of hydrological data are still required.

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