Agricultural and Forest Meteorology 98–99 (1999) 325–340

AGRICULTURAL AND FOREST METEOROLOGY

www.elsevier.com/locate/agrformet

Wetland occurrence in relation to topography: a test of topographic indices as moisture indicators

A. Rodhe*, J. Seibert

Uppsala University, Department of Earth Sciences, Hydrology, Villavägen 16, S-752 36 Uppsala, Sweden

Abstract

Information about the spatial distributions of soil moisture or groundwater levels is needed for aggregation of soil–vegetation–atmosphere–transfer (SVAT) models. The possibility of predicting wetness distributions in catchments from topographic data was investigated using topographic indices, notably the TOPMODEL index. The indices were calculated from commercially available gridded data (50×50 m^2) over two areas with contrasting topography: a catchment (Nåsten) in the low-relief NOPEX region in southern Sweden and a group of catchments in a hilly area (Kassjöån) in central Sweden. The occurrence of mires, assumed to represent the extreme wetness end of the wetness spectrum, was used as field data.

The frequency distributions of topographic indices for mire and non-mires were clearly different in Kassjöån, although there was a large overlapping, whereas the two distributions were very similar in Nåsten. Prediction of mires from topographic indices was meaningful only in Kassjöån. Although it gave poor results in terms of fractions of successfully predicted mire cells out of the observed mire cells, the general spatial patterns of mires were fairly well simulated. One important reason for the failure of the indices to predict mires in Nåsten, and probably also to predict other wetness classes, is that the spatial resolution in the index calculation was coarser than typical length scales of the topographic features in this catchment, being only a few tenths of meters.

The importance of geologic conditions in modifying the topographic control over the wetness is exemplified from the obtained relationship between topographic indices and mire occurrence.

Keywords: Topography; Topographic index; Wetness; Mire; Scale

1. Introduction

The issue of upscaling in hydrological modelling is an area of active research in hydrology (Blöschl and Sivapalan, 1995). As pointed out by Beven (1995), the approach to use formulations that have been derived at small scales directly at larger scales using some 'effective' parameters is not satisfactory. A more reasonable way of upscaling is the aggregation of models developed at small scales over larger areas. For aggregation of soil–vegetation–atmosphere–transfer (SVAT) models, information about the spatial distributions of soil moisture or groundwater levels is needed. Topography has become widely used as a covariate for these distributions in hydrological catch-

* Corresponding author. Tel.: +46-18-471-2256; fax: +46-18-551124.
E-mail address: allan.rodhe@hyd.uu.se (A. Rodhe).

0168-1923/99/$ – see front matter
PII: S0168-1923(99)00104-5

ment modelling, because it has a major impact on the hydrological processes in a catchment and since it is the information for which spatially distributed data is most easily available (Moore et al., 1991).

In the TOPMODEL approach, a topographic index, ln (α/tan β), is used to represent topographical heterogeneity in a simple way, allowing the use of distribution functions (Beven and Kirkby, 1979; Quinn and Beven, 1993). A similar approach has been proposed by O'Loughlin (1986), O'Loughlin (1990). Famiglietti and Wood (1994a) used the TOPMODEL approach to aggregate a SVAT scheme across scales. They used the groundwater level simulated using the TOPMODEL approach as a lower boundary for the one-dimensional SVAT-modelling. A distribution function of the topographic index was then used for a simple aggregation to the macroscale. They applied this multi-scale model on the tallgrass prairie of eastern Kansas (United States) using data collected during the First International Land Surface Climatology Project Field Experiment (FIFE) (Famiglietti and Wood, 1994b). The TOPMODEL approach has also been used as a hydrological framework to extend ecological models over larger areas (Band, 1993; Band et al., 1993; Moore et al., 1993; White and Running, 1994).

The TOPMODEL index attempts to give the areal pattern of the depth to the groundwater table. In areas with shallow groundwater, such as the study areas in this paper, the soil moisture in the upper layers of the ground is, to a large extent, controlled by the depth to the groundwater table. In such areas, the index can be expected to give general information on the spatial pattern of the soil moisture in the root zone, although this pattern is also controlled by the processes determining evapotranspiration. The term 'wetness' is used in this paper in a qualitative sense, referring to both, the depth to the groundwater table and the soil moisture status.

The usefulness of a topographic index approach as a basis for aggregation of SVAT or ecological models over large areas depends on how well the spatial distribution of wetness is captured by the topographic index. However, the predictive power of the TOPMODEL index has not been fully assessed (Blöschl and Sivapalan, 1995). In the few studies, where the distribution of the TOPMODEL index has been compared with distributed field measurements of soil moisture or groundwater levels, the correlation often has been weak (e.g., Burt and Butcher, 1985; Iorgulescu and Jordan, 1994; Moore and Thompson, 1996; Seibert et al., 1997). Thompson and Moore (1996) found that the TOPMODEL index provided more reliable predictions of local groundwater levels than other topographic indices. On the other hand, Crave and Gascuel-Odoux (1997) studied spatial and temporal soil moisture variations and concluded that the restriction to upslope and local topographic conditions limits the ability of the TOPMODEL index to predict wetness distributions correctly. They found that the spatial wetness distribution was controlled by downslope topographic conditions. Merot et al. (1995) compared the TOPMODEL index with the occurrence of different soil types in two catchments with gentle slopes in Brittany. They found a good agreement, at least for the wettest parts of the catchments. Güntner et al. (1997) studied the ability of the TOPMODEL index to predict saturated areas in a mountainous catchment with steep slopes in south-western Germany. Although the general patterns agreed, only one-third of the observed saturated areas could be mapped by the index values. Considering the increasing use of digital elevation models, topographic indices and the TOPMODEL approach, in particular, to simulate spatial wetness distributions in hydrological and ecological models, more studies are needed to assess the quality of these predictions.

The aim of this study was to investigate the possibility to make hydrologically useful predictions of the areal distribution of wetness (soil moisture, depth to the groundwater table) in catchments from the topography, using commercially available topographic data. The occurrence of mires was used as field data for testing the ability of various topographic indices, particularly the TOPMODEL index of Beven and Kirkby (1979), to predict the wetness pattern. The hypothesis was that mires are found mainly at locations characterised by the indices as very wet, and that such locations mainly are mires. The study is based on the assumption that mires represent the extreme wetness end of the wetness spectrum and that a successful prediction of mire locations would suggest that the index also might be able to classify drier locations. Two areas with contrasting topography were selected for the study: one catchment within the low-relief NOPEX area in southern Sweden, and a group of catchments within the more hilly landscape of the former International Hydrological Decade (IHD) representative basin Kassjöån in central Sweden.

2. Material and methods

2.1. Background

Saturated water flow in catchments is driven by gravity. The prerequisite for the force of gravity to generate the flow is the difference in potential energy between the water precipitated over the catchment and the water in the sea, i.e. the height difference between the various points in the landscape and the sea level. The water flow in the unsaturated zone is mainly vertical, but since the transmissivity of the ground is limited, a saturated zone develops in the ground somewhere above the sea level in which the flow is diverted laterally. The smaller the hydraulic conductivity of the ground, the larger fraction of the vertical profile has to be used for this groundwater flow and the larger will be the topographic control of the groundwater surface and soil wetness.

In areas with limited hydraulic conductivity of the deeper layers of the ground, almost the whole vertical cross section of the ground may be needed to transmit the recharged groundwater down through the landscape. Such conditions are, for instance, found in Scandinavian catchments, which commonly have a few meters of till soil on fractured rock. Although the bedrock is not impermeable, its hydraulic conductivity is considerably smaller than that of the topmost till layers. Also, the deeper till layers have comparatively low hydraulic conductivity. For this reason, the depth to the groundwater table seldom exceeds a few meters, which is much less than the typical height differences in the landscape. The groundwater table, therefore, largely follows the topography of the ground surface (Gustafsson, 1968), and the topography has a decisive role in determining the groundwater flow pattern.

If steady-state flow conditions are assumed and the transmissivity variation with depth is known, the depth of the groundwater table, z_g, in an elementary area can be calculated from conditions of continuity and Darcy's law

$$RA = T(z_g) b \frac{dh}{ds} \tag{1}$$

Here, R is the rate of groundwater recharge, A the local catchment area, T the transmissivity of the ground, b the width of the elementary area perpendicular to the slope of the groundwater table, and dh/ds the slope of the groundwater table. In this paper, the depth is denoted by z, with $z = 0$ at the ground surface and the z-axis directed downwards.

In areas with a shallow groundwater table, the slope of the groundwater table can be approximated by the slope of the ground surface, $\tan\beta$. Let us consider two hydraulic conductivity profiles. With a constant hydraulic conductivity, K, down to the depth z_0, below which level the ground is impermeable ($T(z_g) = (z_0 - z_g) K$, $z_g < z_0$), Eq. (1) then gives the depth to the groundwater table as

$$z_g = -\frac{R\alpha}{K \tan\beta} + z_0 \tag{2}$$

where $\alpha = A/b$ is the local catchment area per unit contour length. A more realistic case is when the hydraulic conductivity decreases exponentially with depth, making the transmissivity decrease exponentially with the depth of the groundwater table, $T(z_g) = T_0 \exp(-c z_g)$, where T_0 is the total transmissivity of the ground and c a positive constant. In this case

$$z_g = -\frac{1}{c} \ln \frac{\alpha}{\tan\beta} + \frac{1}{c} \ln \frac{T_0}{R} \tag{3}$$

If the hydraulic conductivity profile and the rate of groundwater recharge are uniform over the area, the height of the groundwater table above a certain reference depth will, thus, be proportional to $\alpha/\tan\beta$ and to $\ln(\alpha/\tan\beta)$, respectively, for the two conductivity profiles. This latter relationship is the basis for the topographic index of TOPMODEL (Beven and Kirkby, 1979; Beven et al., 1995) reading

$$I = \ln(\alpha/\tan\beta) \tag{4}$$

The larger the local catchment area and the smaller the slope, i.e. the higher the value of the index, the less depth to the groundwater table and wetter soil can be expected. The use of the index in this form for calculations of the areal pattern of groundwater levels within a catchment is based on, at least, the following assumptions: The flow conditions are at steady state, the rate of groundwater recharge is uniform over the area, there is no lateral unsaturated flow, the groundwater flow is lateral, the slope of the groundwater table equals that of the ground surface, the conductivity profile is exponential and identical over the area and there is no damming or drainage from downhill, i.e. downhill conditions have no influence on the calculated wetness in an area element.

Considering that the slope of the groundwater table can be expected to be smaller than that of the ground surface in concave hillslopes, due to downhill damming, and correspondingly larger in convex hillslopes, due to downhill drainage, a drainage efficiency gradient was proposed by Hjerdt (1997). The gradient, $\tan \alpha_d$, is defined as the gradient between a point on the ground surface and the nearest point in the downslope direction to which there is a vertical drop of at least d meters. Reasonable values of d have to be assessed from the topography and tested for the purpose of the particular study. In this study, having a spatial resolution of 50 m in the calculations, a value of 2 m was chosen.

Mires can be expected to develop in areas where the water table reaches a certain small depth below the ground surface, z_{m}, which for both conductivity profiles corresponds to a certain value of $\alpha/\tan \beta$. The corresponding value of $\alpha/\tan \beta$ depends on the conductivity profile as seen from Eqs. (2) and (3). The condition for surface saturation ($z_{\mathrm{g}} = 0$) is, on the other hand, given directly from Eq. (1), regardless of the shape of the conductivity profile

$$\frac{\alpha}{\tan \beta} = \frac{T_0}{R} \quad (5)$$

Concerning the slope of the groundwater table, this relationship is less approximate than those giving the depth of the groundwater table. This is so since, under saturated conditions (without significant water storage above the ground), the groundwater table follows the ground surface, so that $\tan \beta$ actually represents the slope of the groundwater table.

2.2. Analysis

Direct information on soil wetness conditions given by commercial Swedish maps is the occurrence of wetland (in Swedish: ‘sankmark’), streams and lakes on the topographic map and the occurrence of peat on geologic maps. In this study, the occurrence of wetland on the topographic map was used as field data on wetness conditions. The database consisted of the topographic map (1 : 50 000, ‘Gröna Kartan’) from the National Land Survey of Sweden. The elevation data were given in a gridded format with an areal resolution of 50 m, interpolated by the National Land Survey from the original contour map. The $50 \times 50\ \mathrm{m}^2$ cells having the points with elevation data in the centre formed the basis for the calculations and subsequent comparisons. The land-use data were given in vector format, and in order to ascribe one land-use class to each cell, the dominating class of each cell was calculated and assumed to represent the cell. The two main wetland classes of the topographic map, ‘temporarily water-logged wetland’ and ‘other wetland’ were lumped together to form one class, called ‘mire’. In order to evaluate the quality of the mapped mire data, wetland occurrence digitised from a map for cross-country running (1 : 25 000, ‘Orienteringskarta’) was used for one of the catchments.

The following indices, calculated for $50 \times 50\ \mathrm{m}^2$ grids, were used in the analysis with the main emphasis put on the TOPMODEL index (as is commonly made, I is calculated for α in m):

- TOPMODEL index, $I = \ln(\alpha/\tan \beta)$
- Slope of the ground surface, $\tan \beta$
- Modified TOPMODEL index, $I_{\mathrm{d}} = \ln(\alpha/\tan \alpha_{\mathrm{d}})$
- Drainage efficiency index, $\tan \alpha_{\mathrm{d}}$

Slope and upslope area per unit contour length can be calculated in different ways (Quinn et al., 1995). The slope, $\tan \beta$, was computed as the mean of all downslope gradients from the cell. The estimation of the upslope area, A, draining to a cell requires a routing of ‘area’ along flow pathways. For this routing, a multiple direction flow algorithm corresponding to that proposed by Quinn et al. (1991) was used. The accumulated area leaving a cell was distributed among all neighbouring downhill cells in proportion to the gradient, i.e. cells in directions with steeper gradients received more area. The upslope area per contour length was then calculated as $\alpha = A/L$, where the contour length L was estimated from the number of neighbouring cells. It should be noted that α has the dimension of length and, thus, the TOPMODEL index depends on the selected length unit. In this study, α is expressed in meters giving I the unit $[\ln(m)]$.

Cells without any adjacent downslope cell, i.e. depressions, are in many TOPMODEL applications 'filled' before the index is calculated. In this study, a different approach was used, treating depressions as real topographic features. The search for downslope cells continued using all cells which were located 2, 3, ... cells away, until at least one downslope cell was found and the area was routed to this/these cell(s). Another problem is the calculation of the topographic index for cells containing streams. For cells drained by a stream, the assumptions underlying the topographic index are not valid, since the flow out of the cell is much larger than that given by the assumed slope of the groundwater table. Therefore, the catchment area needed for forming a stream, A_s, was introduced as a threshold value for channel initiation. This is a simple and the most common method of extracting channel networks from digital elevation models (Montgomery and Foufoula-Georgiou, 1993). Starting from the cell for which the catchment area exceeded A_s, i.e. the assumed start of the stream, all downslope cells following the steepest gradient were marked as stream cells. The catchment area of such cells was only that contributing from the surrounding non-stream cells and the cell itself, i.e. the accumulated area in stream cells was not routed downslope.

The drainage efficiency index, $\tan\alpha_d$, was calculated as L_d/d, where L_d is the distance to the nearest cell having a height $\geq d$ length units below the cell. In contrast to $\tan\beta$, which was calculated as a mean value of downslope gradients, $\tan\alpha_d$ was thus calculated along the steepest direction only.

The relationship between the various topographic indices and the occurrence of mire was investigated in the following ways:

- By visually comparing maps over indices and mire occurrence.
- By comparing the frequency distributions of the indices for mire and non-mire cells. The less overlapping between the distributions, the more unique the relationship between index and mire occurrence.
- By calculating the probability for mire occurrence as a function of the topographic indices. This function is given by the fraction of mire cells of the total number of cells within each index class.
- By defining a threshold value, I_m, for I and I_d, above which the cell was classified as mire. The threshold value was determined from the frequency distribution of the indices for the total land surface (mire and non-mire), assuming that all cells with $I > I_m$, and only those, are mire and that the total mire area is the one given by the map. The threshold value was, thus, taken as the value of the index above which the corresponding land area was equal to the mire area according to the map. A corresponding procedure was applied for $\tan\beta$ and $\tan\alpha_d$. In this case, the threshold value was defined as the value below which a cell was classified as mire, since wet areas are expected to be characterised by small values of the gradients.

The above analyses were all performed on the basic $50 \times 50\ \mathrm{m}^2$ cells, being either classified as non-mire or mire. With this binary classification of the cells, regression analysis between mire occurrence and the indices is not meaningful. In order to allow such a regression analysis, index mean values for $200 \times 200\ \mathrm{m}^2$ cells were compared with the fraction of mire area within the $200 \times 200\ \mathrm{m}^2$ cell as determined from the vector data on land use. It should be noted that the scale for index calculation remained $50 \times 50\ \mathrm{m}^2$, since these mean values of the index were calculated as the arithmetic means of the four $50 \times 50\ \mathrm{m}^2$ index values within the $200 \times 200\ \mathrm{m}^2$ cells. Apart from making regression analysis possible, due to the various mire fractions of the grids, comparisons based on mean values of these larger cells reduced position errors of the mapped mires in relation to the position of the points with elevation data.

A simple interpretation of the threshold values, I_m, in terms of transmissivity was made, assuming that mires occur where the groundwater reaches the ground surface. The condition for surface saturation, Eq. (5), then gives the transmissivity as

$$T_0 = R\frac{\alpha}{\tan\beta} = R\mathrm{e}^{I_m} \tag{6}$$

where R is the rate of groundwater recharge. Noting the high infiltration capacity of the till soils in the study areas as compared to the intensity of rainfall and snowmelt, and the dominating role of groundwater in stream-flow generation in such areas (Rodhe, 1987), R was assumed to equal the mean specific discharge, i.e.

Table 1
Catchment characteristics

Catchment	Area (km^2)		Altitude (m asl)		Mean slope	Mire (% of land area)	Mean precip. (mm per year)	Mean runoff (mm per year)
	including lakes	excluding lakes	maximum	minimum				
Nåsten	6.6	6.6	55	18	0.03	7.7[a]	660	203
Kassjöån	164	155	532	227	0.06	12.4	700	350
Lillhamra							ca. 750	ca. 350
Korsiberget	4.2	4.2	635	445	0.10	12.5		
Hemberget	3.7	3.7	547	441	0.08	3.1		

[a] Percent of non-agricultural land area.

the long-term mean stream discharge per unit catchment area.

2.3. Study sites

Two areas dominated by forested till soil, but with contrasting topography, were selected for the study (Table 1). The Nåsten catchment (see description in Bergqvist, 1971) represents the forest areas of the southern part of the flat NOPEX (Northern Hemisphere Climate Processes Land-Surface Experiment, see Halldin et al., 1999) region in southern Sweden. It is a catchment of low relief with small-scale topographic features. Typical lengths of the hills and valleys in a large part of the forest area are a few tenths of meters. The soil cover is thin and the bedrock, which is dominated by granite, is frequently bare. The catchment includes areas covered with lacustrine clay, mainly coinciding with the land used for agriculture. Agricultural areas were excluded from the analysis, since they are very flat and mostly artificially drained and contain no wetlands.

The Kassjöån catchment, for which the analysis was made compositely for the whole area, as well as separately in 14 subcatchments or parts of subcatchments, is a former IHD representative basin located in central Sweden (see description in Waldenström, 1977). The landscape is moderately hilly, characterised by height differences of typically 50–150 m, with slope lengths of the large-scale topography being typically 0.5–2 km. There are several lakes in the catchment. The soil cover is thin in many elevated areas, where outcrops of limited extension occur. Apart from the dominating till soil there are some minor deposits of gravel and sand. These areas were included in the analysis, which was performed for all land areas. The bedrock varies between the subcatchments, being mainly granite, dolerite and gneiss.

As a complement to the above study areas, two neighbouring sites with forested till soil, near Lillhamra, 140 km SW of Kassjöån, were included in order to illustrate how drainage through the underlying bedrock might influence mire development. The areas, Hemberget and Korsiberget, are not catchments but arbitrarily delineated mountain areas in a landscape similar to that of Kassjöån. According to a visual inspection of the topographic map they have similar topography but, as seen in Table 1, the mire occurrence differs greatly. The bedrock of Korsiberget is less fractured metamorphic andesite, whereas that of Hemberget is highly fractured granite (Minell and Sörvik, 1996).

The 14 analysed subcatchments or parts of subcatchments (henceforth called 'subcatchments' only) in the Kassjöån area have land areas ranging from 2.2 to 48.1 km^2, with a median value of 10.2 km^2. Their fraction of mire area ranges from 4.0 to 21.4% and their mean slope from 7.4 to 12.5%.

3. Results

The catchment area needed for stream channel development, A_s, was determined by trial and error. In Kassjöån a value of 15 ha gave a channel net which agreed reasonably well with that given by the map. The optimal value varied by about ± 5 ha within the area, but since the sensitivity of the further analysis to variations in A_s was small, 15 ha was used in all the Kassjöån subcatchments. This value was also used in the Lillhamra areas and in the Nåsten catchment.

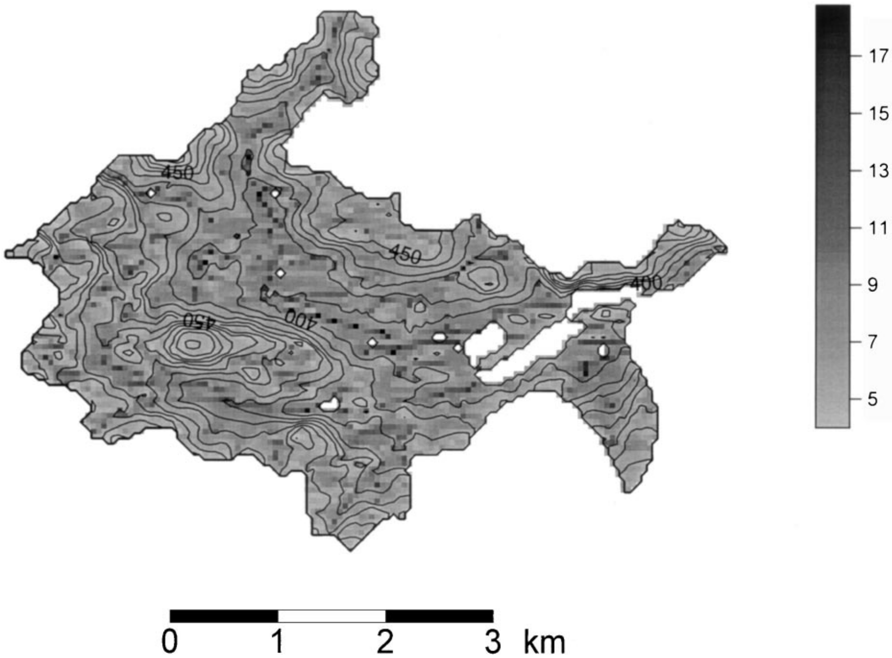

Fig. 1. Topography (m asl, equidistance 10 m) and TOPMODEL index (greyness scale shown) for the Norrsjön catchment, subcatchment to Kassjöån. The white fields enclosed by shaded cells represent lakes.

In Kassjöån and Lillhamra, the areal pattern of the TOPMODEL index agreed roughly with the expected wetness pattern in the catchments (see the map over one of the subcatchments in Kassjöån, the Norrsjön catchment, in Fig. 1 for an example). Ridges were characterised by low values, whereas lower parts of hillslopes, particularly concave landforms and valley bottoms, had high values. In Nåsten the calculated index failed to show the wetness pattern. This is seen directly from Fig. 2, showing that mires occur at any index class and not predominantly in areas with high indices.

In Kassjöån and Lillhamra, the frequency distributions of the various topographic indices for cells classified as mires and non-mires were clearly different, but in Nåsten the two distributions were very similar (Figs. 3 and 4, Table 2). Although the median values of both the distributions differed in Kassjöån and Lillhamra, there was a large overlapping between the distributions, showing that there was far from a unique relationship between the indices and mire occurrence. The overlapping varied between the subcatchments in Kassjöån, which was reflected by considerable variations in the difference between the median values of the indices of the two populations when calculated separately for each subcatchment (Table 3).

The strength of the various indices as mire indicators depends on the difference between the two distributions. One objective measure of this difference is the Kolmogorov–Smirnov *D*-variable (Press et al., 1993), being 0 for identical and 1 for completely separated distributions, i.e. distributions with no overlapping. According to this measure, being around 0.5–0.6 for the various indices in Kassjöån and Lillhamra, $\tan\beta$ gave the most separated distributions (Tables 2 and 3).

The probability of mire occurrence as a function of the various indices, defined as the fraction of mire cells of the total number of cells within each index class, is obtained from the frequency distributions of the two populations and the fraction of mire area. For completely separated distributions, the probability would have two values only, being 0 for indices below and 1 for indices above the threshold value for mire occurrence. For identical distributions, the fraction would be equal to the total fraction of mire area for all indices. With the more or less overlapping distribu-

Fig. 2. Observed mires (white polygons) and TOPMODEL index (greyness scale is given in Fig. 1) for the Nåsten catchment. The white fields enclosed by shaded cells represent agricultural land (or, in a few cases, lakes), which were excluded from the analysis.

tions found here, the probability varied gradually. In Kassjöån, the probability given by the TOPMODEL index increased to a fairly constant value around 0.5 at high indices. The nearly similar index distributions for mires and non-mires in Nåsten gave a small probability for mire occurrence over the whole index range (Fig. 5), only moderately deviating from the fraction of mire area of the catchment. In the Lillhamra area, the number of cells were too small to make meaningful probability distributions.

The similarity of the distributions in Nåsten shows that in this catchment, with the present spatial resolution in the calculations, the attempted indices cannot be used for mire prediction and, probably, neither for wetness classification in general. Nåsten is, therefore, excluded from the further analysis of the indices.

The threshold values for mire occurrence, determined for the various indices, varied among the different investigated areas. The TOPMODEL index threshold value ranged from 9.2 to 11.5 in Kassjöån subcatchments and the Lillhamra area (Tables 2 and 3). (The values for Nåsten are given in Table 2 for comparison, but they are considered to be of little significance.) The mires in the Norrsjön subcatchment of Kassjöån, predicted by this simple model using TOPMODEL index, is shown together with the mires according to the topographic map in Fig. 6. Such a comparison gives possibilities to analyse, for instance, the locations of successfully and unsuccessfully predicted mires, i.e. mires at locations with high and low topographic indices, etc. A quantitative measure of the accuracy of the prediction of mire occurrence is the

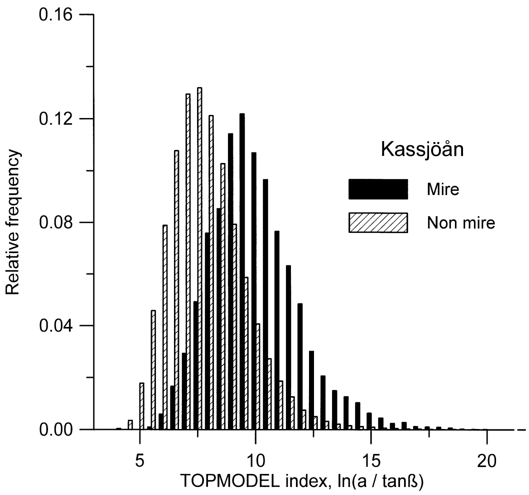

Fig. 3. Frequency distributions of the TOPMODEL index for mire and non-mire cells (Kassjöån catchment).

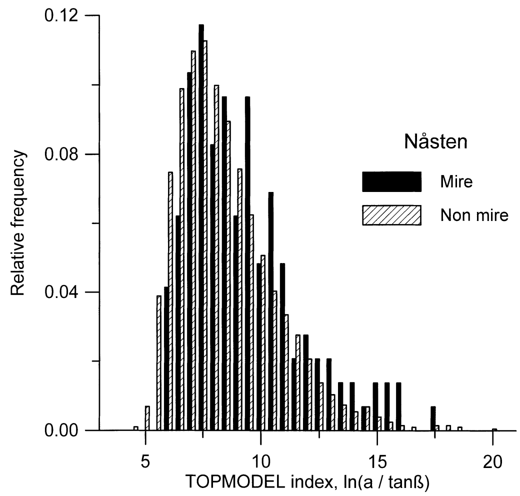

Fig. 4. Frequency distributions of the TOPMODEL index for mire and non-mire cells (Nåsten catchment).

fraction of successful mire predictions of the total mire occurrence according to the topographic map. This fraction can be obtained from maps, such as Fig. 6, but also directly from the separation of the frequency distributions of topographic indices for mires and non-mires (e.g. Figs. 3 and 4) together with the total fraction of mire area. If there were no overlapping between the distributions, the fraction would be 1.0. For the TOPMODEL index the fraction is given by the number of mire cells with $I > I_m$ minus the number of non-mire cells with $I > I_m$ divided by the total number of mire cells. When looking at the whole Kassjöån catchment, the fraction of successful mire predictions was 0.40 for the TOPMODEL index and

Table 2
Characteristics of the various topographic indices for mire and non-mire cells for Kassjöån, Nåsten and Lillhamra

Catchment	Topographic index				K.—S[a]. *D*-variable	Threshold value for mire	Fraction of mires successfully predicted
	mean total area	median		difference (a–b)			
		mire (a)	non-mire (b)				
Kassjöån							
I	8.15	9.65	7.59	2.06	0.48	10.11	0.40
I_d	7.81	9.27	7.30	1.97	0.46	9.83	0.40
Tanβ	0.058	0.014	0.051	−0.037	0.57	0.0145	0.44
Tan β_d	0.077	0.022	0.066	−0.044	0.54	0.0228	0.46
Nåsten							
I	8.50	8.51	7.90	0.61	0.14	11.90	0.14
I_d	8.15	7.91	7.31	0.60	0.14	11.70	0.15
Tan β	0.035	0.013	0.020	−0.007	0.28	0.0056	0.13
Tan β_d	0.036	0.019	0.030	−0.011	0.26	0.0074	0.14
Korsiberget							
I	7.43					9.15	0.42
Hemberget							
I	7.92					10.80	0.27

[a] Kolmogorov–Smirnov.

Table 3
Statistical properties of results from calculations made separately for the 14 subcatchments of Kassjöån

	Index type	Mean	Range	Standard deviation
Difference between median values for mire and non-mire	I	2.28	1.88–3.32	0.38
	Tan β	−0.040	−0.060–0.030	0.008
	Tan β_d	−0.046	−0.066–0.037	0.008
Kolmogorov—Smirnov D-variable	I	0.51	0.43–0.66	0.06
	Tan β	0.61	0.55–0.69	0.04
	Tan β_d	0.59	0.49–0.73	0.06
Threshold value for mire occurrence	I	10.41	9.35–11.46	0.60
	Tan β	0.011	0.003–0.023	0.005
	Tan β_d	0.017	0.002–0.031	0.007
Fraction of mires successfully predicted	I	0.41	0.21–0.55	0.09
	Tan β	0.41	0.11–0.86	0.16
	Tan β_d	0.41	0.21–0.57	0.11

its modified version, and somewhat higher for the slope indices. The fractions varied considerably among the subcatchments, particularly for the slope indices (Table 3).

The percentage of mire area varies largely among the Kassjöån subcatchments, ranging from 4 to 21%. If the occurrence of mire were determined by the topographic index, catchments with a large fraction of mire would have a comparatively large fraction of cells with high topographic indices. Such a relationship, although weak, can be seen in Fig. 7, in which the

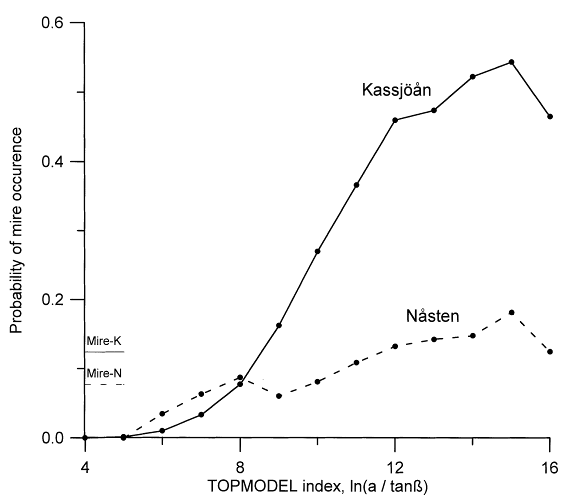

Fig. 5. Probability of mire occurrence as a function of TOPMODEL index values (Kassjöån and Nåsten catchments).

fraction of cells with topographic indices above certain attempted threshold values around the obtained threshold values for mire occurrence are plotted against the fraction of mire area. The slope of the regression lines are small as compared with the 1 : 1 line that would have been obtained if the threshold value were constant among the subcatchments. The diagram shows that the fraction of mire area varies much more than the fraction of cells with high indices, implying that the threshold values for mire occurrence decreases with increasing fraction of mire area.

Each value on the horizontal axis in the diagram represents a subcatchment, by its observed mire fraction. Actual threshold values would give data points on the 1 : 1 line, i.e. the calculated and observed mire fractions would agree. Such values can be roughly interpolated from the three data points shown for each catchment. It can be seen, for example, that the catchment with the largest mire fraction has a threshold value around 9.3. A high negative linear correlation ($r^2 = 0.86$) was obtained between the threshold values and the observed fraction of mire area for the subcatchments of Kassjöån (figure not shown).

Linear regression between the fraction of mire area and mean values of the indices within 200 × 200 m^2 cells in Kassjöån gave the expected signs of the relationship (see Fig. 8 for an example). The correlation is, however, weak with $r^2 = 0.31$ for ln (α/tan β) and lower values for the other indices. As seen directly from the diagram, the value of the relationship for mire prediction is very small.

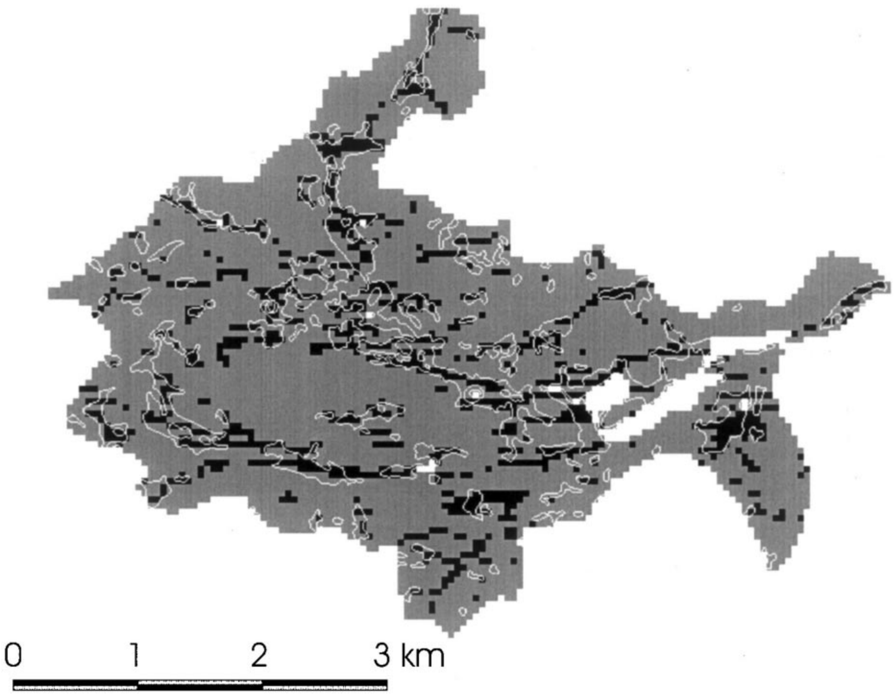

Fig. 6. Predicted (black cells) and observed mires (white polygans) (Norrsjön catchment, subcatchment of Kassjöån). The white fields enclosed by shaded cells represent lakes.

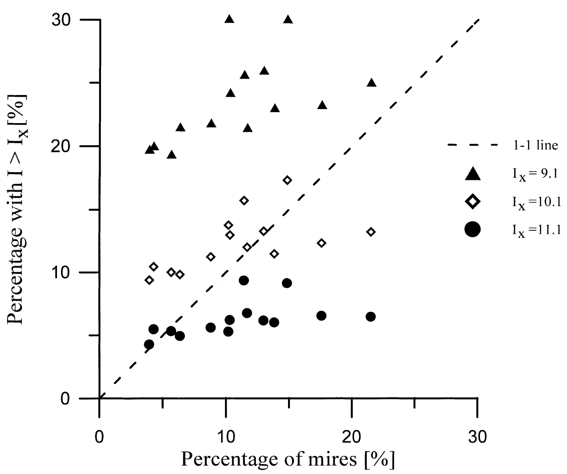

Fig. 7. Percentage of area with TOPMODEL index (I) larger than certain values (I_x) around the global mean threshold value for mire occurrence in the Kassjöån basin ($I_m = 1.11$) vs. percentage of mires for the 14 subcatchments in the basin.

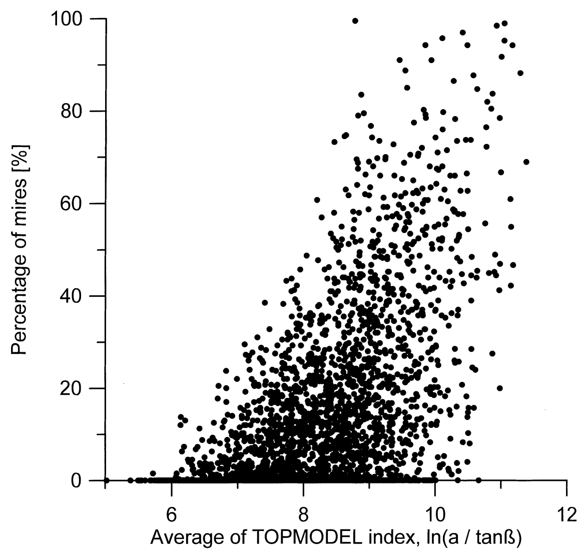

Fig. 8. Mire percentage against average values of the TOPMODEL index for areas of $200 \times 200\ m^2$ in the Kassjöån basin. The index values represent mean values of the $50 \times 50\ m^2$ index values calulated for the four cells within each $200 \times 200\ m^2$ cell.

4. Discussion

There is little general interest in predicting the occurrence of mires from the topography, since good maps over mires already exist. The aim of this study was to test the ability of various topographic indices to predict the areal pattern of wetness in general, such as soil moisture status and depth to the groundwater table. Mires were used as field validation data, since their occurrence was easily available from maps in contrast to, for instance, groundwater levels. As mentioned above, the underlying assumption was that mires represent the extreme wet end of the wetness spectrum, and that a successful prediction of mire occurrence would suggest that the index also might be able to predict the areal pattern of the drier wetness classes.

The basic condition for a successful mire prediction from a topographic index is that the frequency distributions of the indices for non-mire and mire cells are different. Although there was considerable overlapping, the two distributions were clearly different for the attempted indices in Kassjöån and Lillhamra. In Nåsten, on the other hand, the difference between the distributions was small and practically no information on mire occurrence was obtained from the calculated indices. One important reason for the failure of the indices to predict mires in Nåsten is that the spatial resolution in the present index calculations (50×50 m^2) is coarser than typical length scales of the topographic features in this catchment, being only a few tenths of meters. The calculations of local catchment area, α, and slope, tan β, are thus of limited value. The hydraulic conductivity of the ground in Nåsten is, furthermore, highly heterogeneous. The soils are very shallow in many areas and the groundwater is frequently dammed by the bedrock, thus violating the assumption underlying the TOPMODEL index on an areally constant conductivity profile.

Of the different indices, the slope indices seem to give slightly better separations and mire prediction results than the TOPMODEL index (Tables 2 and 3). The introduction of the drainage efficiency index, tan α_{d}, and the resulting modification of the TOPMODEL index, I_{d}, gave no, or very small improvement concerning the above criteria (Table 2). Although the slope indices were slightly better for mire prediction, the TOPMODEL index is of more general interest since it is physically more connected with the depth to the groundwater table than is the slope alone. This paper, therefore, focuses on the TOPMODEL index.

Considering the non-unique relationship between the indices and mire occurrence in Kassjöån and Lillhamra, shown by the overlapping between the frequency distribution curves of the indices for mire and non-mire cells, a close agreement between predicted and observed mires could not possibly be expected with the simple model based on threshold values for mire occurrence. Although the quantitative measure on model success showed poor results, with about 40% of the observed mires being successfully predicted (Tables 2 and 3), the areal patterns of the indices and of observed mires showed some basic similarities. Areas with high TOPMODEL indices mostly included areas classified as mires on the map, or were in the vicinity of such areas. There were, however, several deviations from this relationship, i.e. cells with high topographic index not classified as mires and cells classified as mires, but expected to be dry according to the index (e.g. Fig. 6). Reasons for the deviations can, at least, be related to the following themes, which are enumerated below:

- The validity of the TOPMODEL index as wetness indicator
- Scale and areal resolution
- Methodology for calculation of the index
- Field data on mires
- Mire formation processes — relevance of the index for mire prediction

The problem of using the TOPMODEL index as a wetness indicator, in this study as well as in most other studies, is related to the first two themes. Noting this, we still devote a large part of the discussion on the mire data, since they are the field data used for validation in this particular study.

Several simplifying assumptions underlying the use of the topographic index of Beven and Kirkby (1979) for prediction of the wetness pattern within a catchment were mentioned earlier in this paper. All of these are more or less violated in a real catchment. The most important violation, in this study, is probably the one concerning the assumption on a uniform hydraulic conductivity profile over the area. With the inhomogeneous till soil, varying soil depth, various underlying rock and occurrences of bare bedrock as well as deposits of other soils than the dominating till, there must be large variations in the conductivity profile. A visible effect of this variation is the damming of surface water and groundwater by exposed bedrock commented upon earlier for Nåsten catchment.

The spatial resolution of topographic data is a key factor for index calculations. How relevant are calculations on a $50 \times 50\ \mathrm{m}^2$ basis in the landscapes under study? The distribution of the topographic index over a certain area has been found to be sensitive to the degree of spatial resolution used in the calculations (Wolock and Price, 1994; Saulnier et al., 1997). The coarser the grid net, the higher is the areal mean of the index. This relationship is not evident for the local catchment area, α, but it is evident for the slope since small-scale topographic irregularities, tending to increase the calculated mean slope of the landscape, disappear as the grid size increases, giving less slope and, thereby, a larger topographic index. The spatial resolution of the calculations must be in accordance with the resolution of the landscape properties that determines the groundwater level. As commented above, this condition was not fulfilled for Nåsten. In Kassjöån, a $50 \times 50\ \mathrm{m}^2$ resolution fairly well describes the topography in much of the area, although exceptions frequently occur. Field control of some of the mires not predicted by the model showed that they were located in narrow depressions or just beneath steep slopes, with large possibilities for erratic slope calculations with a $50 \times 50\ \mathrm{m}^2$ resolution.

One methodological problem is the treatment of stream cells. Mires were predicted along the streams in many valley bottoms, although there are no mires according to the map (see, e.g. the black diagonal in the lowest part of Fig. 6). The introduction of an upper limit for the catchment area routed to a stream cell, A_s, determined as the area needed for stream channel development, reduced but did not eliminate this deviation. On the other hand, the groundwater table is probably very close to the ground surface near the streams in these landscapes, and there may also be narrow strips of peatland along the streams, not shown as mires in the topographic map. The existence of a stream in a cell can be seen as giving the section a very high hydraulic conductivity, violating the constant conductivity profile assumption and lowering the groundwater table.

The accuracy of the mapping of mires in the topographic map is not known. In Nåsten, the mire fraction was considerably smaller according to the used topographic map (1 : 50 000) than according to the map for cross country running (1 : 25 000), being 7.7 and 11.7% of the non-agricultural land, respectively. With the present resolution in topographic data, however, the ability of the indices to describe the mire pattern in Nåsten did not improve when mires from the 1 : 25 000 map were used instead of those from the 1 : 50 000 map.

A possible reason for discrepancies in this study could be errors in the position of the mapped mires in relation to the position of the topographic data points. This error was reduced in the regression analysis, performed in Kassjöån for $200 \times 200\ \mathrm{m}^2$ cells (Fig. 8). The large scatter in the data points of Fig. 8 showed, however, that even with reduced effect of position errors there was a weak agreement between mire occurrence and value of the topographic index.

The minimum size for a mire to be presented in the used topographic map is $2500\ \mathrm{m}^2$, i.e. equal to the grid size used in this study. We classified a cell as a mire cell if more than half of the cell area, i.e. $>1250\ \mathrm{m}^2$, is defined as mire according to the map. This discrepancy might give erroneous classification of some isolated real mires, having areas between 1250 and $2500\ \mathrm{m}^2$, where the corresponding cell should have been classified as mire although the mire is not shown by the map. These errors are probably of little importance.

An implicit assumption in the attempts to relate mire occurrence to topographic indices is that the mapped mires are the only wet areas. The definition of mires (or rather the Swedish word 'sandmark' (wetland)) in the map is not clear. It is probably related to surface saturation during extended periods, which in the landscape of Kassjöån mostly is connected with peatland and a characteristic peatland vegetation. Field control of a few areas in Kassjöån, classified as mires according to the TOPMODEL index, but as non-mire by the map, showed that several of them were typical discharge areas for groundwater, with a shallow water table and signs of temporary surface saturation, characteristic vegetation and a thick organic layer. The field control showed that several non-mire cells with topographic index above the threshold value for mire occurrence could be classified as wet. The limited field control performed in this study does not, however, allow a quantification of this extension of the wet areas. One reason why mires develop in certain wet locations, but not in other, is probably related to the length of periods with surface saturation and to the depth of the water table during dry periods. With periods of surface saturation separated by long periods of low water table, the decomposition of the organic material may be sufficient to prevent development of a peat layer. Such temporal variations of the groundwater table are not considered by the TOPMODEL index while attempting to give the spatial pattern of the relative depths to the groundwater table in an ideal catchment during steady-state flow conditions.

A fundamental objection could be raised against the use of mires as field data to test the ability of topographic indices to predict the wetness pattern in catchments. Many mires (but not all) have developed as a result of damming, giving flat ground surfaces and, consequently, high TOPMODEL index values, regardless of the upslope topography. This may be one reason for the slightly better model performance when using $\tan\beta$ instead of $\ln(\alpha/\tan\beta)$ as a wetness index. Furthermore, the development of mires was once initiated at locations where there was an excess of water, i.e. at locations that were probably characterised by high TOPMODEL index (although a possible relationship between topographic index and mire occurrence should have changed over time due to historical climate variations and vegetation changes). After the initial formation, however, the mire may have changed the topographic index of the location, since it forms its own ground surface by biological activity. Parts of raised bogs, for instance, might have a comparatively small TOPMODEL index due to a small local catchment area (being only a fraction of the central part of the bog). Another disadvantage of using mires is the difference in the hydraulic conductivity between mineral soil and peat, inherently violating the assumption of a constant hydraulic conductivity profile over the catchment.

One reason for the varying threshold values for mire occurrence obtained for the different subcatchments of Kassjöån (Table 3, Fig. 7) is probably related to variations in the hydraulic conductivity of the soil and the underlying bedrock. With an areally constant rate of groundwater recharge, the value of $\alpha/\tan\beta$ needed for surface saturation will increase with an increased transmissivity of the ground (Eq. (5)). The threshold value I_m could, therefore, be expected to be largest in areas having the most conductive ground. (In the derivation of the TOPMODEL index, the Dupuit assumption is used, i.e. only lateral groundwater flow is considered. A vertical drainage, due to highly conductive bedrock, is not considered, but it will have a similar effect as a high transmissivity.) The range of threshold values, I_m, among the subcatchments of Kassjöån, $9.2 \leq I_m \leq 11.5$, together with an annual mean rate of groundwater recharge of 350 mm per year, corresponds by Eq. (6) to transmissivity values at surface saturation ranging from 1×10^{-4} to $1 \times 10^{-3}\ m^2\ s^{-1}$. We have no field data on hydraulic conductivity or transmissivity from the area, but the estimated transmissivity values are about one order of magnitude larger than those derived from conductivity values in till soil in comparable Swedish areas (Lundin, 1982; Bishop, 1991).

The available geologic information in the Kassjöån area does not allow a detailed investigation of a possible relationship between geologic conditions and threshold values, although Hjerdt (1997) found an indicative relationship between I_m and bedrock geology in the area. A striking example of different threshold values, most probably caused by differences in the bedrock geology, is, however, given by the two neighbouring mountain areas in Lillhamra. Although the topography of the two areas is fairly similar, according to a visual inspection of the topographic map, the fraction of mire area differs greatly (Fig. 9 and Table 1). It is, therefore, not surprising that there is a considerable difference in threshold values for mire occurrence (Table 2). The different mire occurrence agrees with differences in bedrock geology, with the bedrock of the mire-rich Korsiberget being metamorphic andesite as compared to the more conductive highly fractured granite of Hemberget. Using the obtained threshold values and the annual rate of groundwater recharge (Table 1) Eq. (6) gives a transmissivity of $1 \times 10^{-4}\ m^2\ s^{-1}$ in Korsiberget and $5 \times 10^{-4}\ m^2\ s^{-1}$ in Hemberget.

5. Conclusions

Practically useful relationships between topography and groundwater levels would be of great interest. A

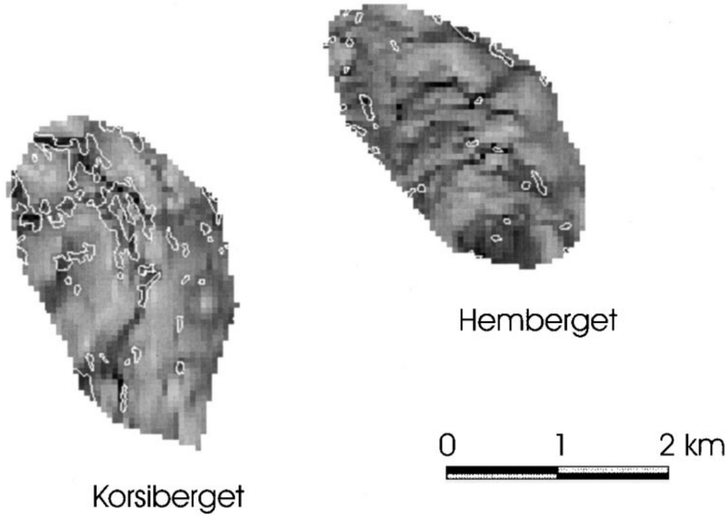

Fig. 9. Observed mires (white polygons) and TOPMODEL index (greyness scale given in Fig. 1) in two neighbouring mountain areas with different bedrock geologies.

first pre-requisite for such relationships to exist is that the spatial resolution of the topographic data gives a useful description of the topography from the point of view of groundwater flow. This study shows that topographic indices calculated from commercially available elevation data, having a resolution of $50 \times 50\,m^2$, do not describe the wetness pattern in the Nåsten catchment, and thus probably not in much of the forested areas in the NOPEX region. The main reason for the failure is the fact that the length scale of the topographic features and the wetness pattern in this landscape is smaller than 50 m. It can be concluded that aggregation of SVAT models using TOPMODEL index calculated from $50 \times 50\,m^2$ topographic data is not meaningful in much of the NOPEX area. In the Kassjöån catchment, which has a more pronounced topography with a larger length scale, $50 \times 50\,m^2$ topographic data gave a partly successful prediction of mires. The result supports the possibility that such data can be used also for prediction of drier wetness classes in the area, but this must be investigated by field studies.

Topographic data with a higher spatial resolution might give a better description of the wetness pattern in the investigated areas. Regarding the influence of geologic conditions, indicated here by the different threshold values for mire occurrence, any simple relationship between topography and soil wetness must, however, be used with great care.

Acknowledgements

This work has been carried out within the framework of NOPEX — a Northern Hemisphere climate Processes land-surface Experiment. The authors thank Niclas Hjerdt for valuable discussions. The work was supported by Swedish Natural Science Research Council, Contract No. G-AA/GU 01656-307.

References

Band, L.E., 1993. Effect of land surface representation on forest water and carbon budgets. J. Hydrol. 150, 749–772.

Band, L.E., Patterson, P., Nemani, R., Running, S.W., 1993. Forest ecosystem processes at the watershed scale: incorporating hillslope hydrology. Agric. For. Meteorol. 63, 93–126.

Bergqvist, E., 1971. Nåsten and Marsta — two small drainage basins in central Sweden. 1. Purpose of the investigation and description of the basins. UNGI Report 5, Uppsala Univ., Dept Phys. Geogr. (In Swedish with English summary and figure captions).

Beven, K.J., 1995. Linking parameters across scales subgrid parameterizations and scale dependent hydrological models. Hydrolog. Processes 9, 507–525.

Beven, K.J., Kirkby, M.J., 1979. A physically based, variable contributing area model of basin hydrology. Hydrolog. Sci. — Bulletin des Sciences Hydrologiques 24, 43–69.

Beven, K.J., Lamb, R., Quinn, P.F., Romanowicz, R., Freer, J., 1995. In: Singh, V.P. (Ed.), Computer Models of Watershed Hydrology, Water Resources Publications, Highlands Ranch, CO, USA TOPMODEL (Chapter 18, pp. 627–668).

Bishop, K.H., 1991. Episodic increase in stream acidity, catchment flow pathways and hydrograph separation, Ph.D. thesis, Cambridge University.

Blöschl, G., Sivapalan, M., 1995. Scale issues in hydrological modelling: a review. Hydrolog. Processes 9, 251–290.

Burt, T.P., Butcher, D.P., 1985. Topographic controls of soil moisture distribution. J. Soil Sci. 36, 469–486.

Crave, A., Gascuel-Odoux, C., 1997. The influence of topography on time and space distribution of soil surface water content. Hydrolog. Processes 11, 203–210.

Famiglietti, J.S., Wood, E.F., 1994a. Multiscale modeling of spatially variable water and energy balance processes. Water Resources Res. 30(11), 3061–3078.

Famiglietti, J.S., Wood, E.F., 1994b. Application of multiscale water and energy balance models on a tallgrass prairie. Water Resources Res. 30(11), 3079–3093.

Gustafsson, Y., 1968. The influence of topography on groundwater formation, In: Eriksson, E., Gustafsson, Y., Nilsson, K. (Eds.), Groundwater Problems, Pergamon Press, Oxford, pp. 3–21.

Güntner, A., Uhlenbrook, S., Seibert, J., Leibundgut, C., 1997. In: Diekkrüger, B., Richter, O. (Eds.), Estimation of Saturation Excess Overland Flow Areas — Comparison of Topographic Index Calculations with Field Mapping Catchments (extended abstract), International Conference on Regionalization in Hydrology, Institute of Geography and Geoecology, Technical University Braunschweig, Germany.

Halldin, S., Gryning, S.E., Gottschalk, L., Jochum, A., Lundin, L.C., Van de Griend, A.A.. 1999. Energy, water and carbon exchange in a boreal forest — NOPEX experiences, J. Agric. For. Meteorol. 98–99, 5–29.

Hjerdt, N., 1997. Soil moisture distribution from topography and gamma radiation. Thesis paper (Examensarbete) Department of Earth Sciences, Hydrology, Uppsala University, Sweden.

Iorgulescu, I., Jordan, J.-P., 1994. Validation of TOPMODEL on a small Swiss catchment. J. Hydrol. 159, 255–273.

Lundin, L., 1982. Mark- och grundvatten i moränmark och marktypens betydelse för avrinningen [Soil moisture and groundwater in till soil and the significance of soil type for runoff]. UNGI Report 56, Uppsala University, Dept Physical Geography (in Swedish with English summary and figure legends).

Merot, Ph., Ezzahar, B., Walter, C., Aurousseau, P., 1995. Mapping waterlogging of soils using digital terrain models. Hydrolog. Processes 9, 27–34.

Minell, H., Sörvik, B., 1996. Ståndortsbonitering med hjälp av fjärranalys och GIS, Nämnden för Skoglig fjärrananlys [Forest bonity estimates from remote sensing and GIS], Gävle, Sweden (in Swedish).

Montgomery, D.R., Foufoula-Georgiou, E., 1993. Channel network source representation using digital elevation models. Water Resources Res. 29(12), 3925–3934.

Moore, I.D., Grayson, R.B., Ladson, A.R., 1991. Digital terrain modelling: a review of hydrological, geomorphological, and biological applications. Hydrolog. Processes 5, 3–30.

Moore, I.D., Norton, T.W., Williams, J.E., 1993. Modelling environmental heterogeneity in forested landscapes. J. Hydrol. 150, 717–747.

Moore, R.D., Thompson, J.C., 1996. Are water table variations in a shallow forest soil consistent with the TOPMODEL concept. Water Resources Res. 32(3), 663–669.

O'Loughlin, E.M., 1986. Prediction of surface saturation zones in natural catchments by topographic analysis. Water Resources Res. 22(5), 794–804.

O'Loughlin, E.M., 1990. Modelling soil water status in complex terrain. Agric. For. Meteorol. 50, 23–38.

Press, W.H., Flannery, B.P., Teukolsky, S.A., Vetterling, W.T., 1993. Numerical Recipes in Pascal: The Art of Scientific Computing, second ed., Cambridge University Press.

Quinn, P.F., Beven, K.J., Chevallier, P., Planchon, O., 1991. The prediction of hillslope flowpaths for distributed modelling using digital terrain models. Hydrolog. Processes 5, 59–80.

Quinn, P.F., Beven, K.J., Lamb, R., 1995. The ln(α/tanβ) index: How to calculate it and how to use it within the TOPMODEL framework. Hydrolog. Processes 9, 161–182.

Quinn, P.F., Beven, K.J., 1993. Spatial and temporal predictions of soil moisture dynamics, runoff, variable source areas and evapotranspiration for Plynlimon, Mid-Wales. Hydrolog. Processes 7, 425–448.

Rodhe, A., 1987. The origin of streamwater traced by oxygen-18. Ph.D. Thesis, Uppsala University, UNGI Report Series A No. 41, Uppsala, Sweden.

Saulnier, G.-M., Beven, K.J., Obled, Ch., 1997. Digital elevation analysis for distributed hydrological modeling: reducing scale dependence in effective hydraulic conductivity values. Water Resources Res. 33(9), 2097–2101.

Seibert, J., Bishop, K., Nyberg, L., 1997. A test of TOPMODEL's ability to predict spatially distributed groundwater levels. Hydrolog. Processes 11, 1131–1144.

Thompson, J.C., Moore, R.D., 1996. Relations between topography and water table depth in a shallow forest soil. Hydrolog. Processes 10, 1513–1525.

Waldenström, A., 1977. Slutrapport över hydrologiska undersökningar i Kassjöåns representativa område [Final report on hydrological studies in the representative basin Kassjöån]. HB Rapport nr 29, Swedish Meteorological Institute SMHI, Norrköping, Sweden (in Swedish with English description of the area).

Wolock, D.M., Price, C.V., 1994. Effects of digital elevation model map scale and data resolution on a topography-based watershed model. Water Resources Res. 30, 3041–3052.

White, J.D., Running, S.W., 1994. Testing scale dependent assumptions in regional ecosystem simulations. J. Veg. Sci. 5, 687–702.